SCINTILLATOR DIAGNOSTICS FOR THE DETECTION OF LASER ACCELERATED ION BEAMS *

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Abstract

Radiation pressure acceleration with ultraintense laser pulses presents an exciting new scheme for accelerating ions. One of the advantages conferred by using a gaseous laser and target is the potential for a fast (several Hz) repetition rate. This requires diagnostics which are not only comprehensive for a single shot, but also capable of repeated use. We consider several scintillators as candidates for an imaging diagnostic for protons accelerated to MeV energies by a CO_2 laser focused on a gas jet target. We have measured the response of chromium-doped alumina (Chromox), CsI:Tl, and polyvinyl toluene (PVT) screens to protons in the $2-8$ MeV range using a CCD camera. We have calibrated the luminescent yield in terms of photons emitted per incident proton for each scintillator. We also discuss how light scattering and material properties affect detector resolution. Furthermore, we consider material damage and the presence of an afterglow under intense exposures. Our analysis reveals a near order of magnitude greater yield from Chromox in response to proton beams at > 5 MeV energies, while scattering effects favor PVT at lower energies.

INTRODUCTION

Acceleration of protons by intense laser pulses has become an increasingly active area of study amongst nuclear, plasma, and accelerator physicists. Recent experiments with intense CO_2 laser pulses have produced collimated bunches of protons with energies greater than 1 MeV and narrow energy spread with the potential to do so at repetition rates on the order of $1-10$ Hz [1] [2]. The evolving nature of this field necessitates flexible diagnostic techniques suited to measure a myriad of experimental outputs.

Film and resin diagnostics offer single particle sensitivity but require weeks of analysis. MCPs offer a controlled gain curve and excellent resolution but are extremely delicate and ill-suited to high energy radiation. The use of scintillators has emerged as a flexible diagnostic as they may exhibit strong luminescence in response to an array of radiation types and energies; nonetheless their use necessitates precise calibration and their specific responses may vary by orders of magnitude [3]. The goal of these tests was to find a material which produces an adequate and consistent light yield under expected conditions ($10^4 - 10^6$ protons

with energies $\sim 1-20$ MeV). The material should have sufficient resolution to determine bunch size, and should be relatively inexpensive and robust when exposed to high radiation flux at a repetition rate near 1 Hz.

EXPERIMENTAL METHOD

We narrowed our potential candidates to three scintillators: Chromox, CsI:Tl, and PVT. Chromox ($Al_2O_3 : Cr_2O_3$) is a ceramic phosphor designed to be durable under high radiation exposure and is responsive to ions in the MeV range [4] [5]. Chromox emits at $\sim$693 nm. CsI:Tl is an inorganic crystal scintillator which emits at 550 nm. Though designed for photon detection, it's high-Z composition improves proton stopping power and makes it a high yield candidate. PVT is a low Z organic compound comprised of covalently bonded vinyl toluene chains, and as such it is easily damaged by high linear energy transfer (LET) radiation [6] [7]. BC-416 is the specific PVT variant tested, featuring added fluorophores as solvents to adjust the emission spectrum. It emits light through several channels, due to the presence of several solvents; the maximum of its emission spectrum occurs at 434nm, and its stated decay time is 4 ns.

We obtained a 1 inch diameter, 0.82 mm thick Chromox disc from Morgan Advanced Ceramics. We evaporated a 225 nm thick aluminium coating on the disc to diminish noise from electrons and X-rays. An uncoated 25 mm diameter by 1 mm thick CsI:Tl disc was purchased from Marketech International Ltd. The plastic scintillator is a 2" $\times$ 2" square, 1 mm thick, with a 50 μm Al coat, and has been used for previous proton experiments at the Accelerator Test Facility at BNL.

Experiments were performed at Stony Brook University using the Stony Brook Tandem Van de Graaff. Protons may be accelerated to total energies of $2-12$ MeV with 0.01% accuracy. Beam currents are flexible from 200 pA to 8.0 nA. Current regulation limits instantaneous uncertainties to no less than 10% regardless of beam parameters.

We used a Basler scA1400-17gm monochrome CCD camera to image the scintillator output. It features a 58% quantum efficiency at 545 nm, 12-bit image depth, and a 1392×1040 pixels sensor with 6.45μm $\times$ 6.45μm pixel size. The camera is paired with 75 mm $f\#/1.4$ tv-lens which corresponds to a maximum aperture of 0.414 sr.

RESULTS AND ANALYSIS

Captured images are analyzed following the European Machine Vision Association (EMVA) Model 1288 [8]. 300

images were taken for each camera setting after specifying a 200x200 pixel A.O.I, from which an average background subtracted grey value was obtained, correlating the luminescence due to scintillation for given beam parameters. An average yield was then calculated using the EMVA Model given the optical parameters of our setup. A Lambertian falloff of light intensity versus the angle, θ, between the scintillator surface and the camera is assumed. This contributes a factor of $\cos\theta$ to the model. We define the yield according to

$$Y = \frac{\mu_\gamma}{f_\gamma N_p} \qquad (1)$$

$$\text{and} \qquad f_\gamma = \frac{\Omega}{4\pi} T_w \cos\theta$$

where f_γ is the fraction of photons collected by the camera, which is a function of solid angle, Ω, weighted transparency of insertion devices, T_w, and θ. The yield Y then depends on $f\gamma$, N_p the number of protons, and μ_γ, the number of photons collected per pixel by the camera.

Table 1: Raw Photon Yields for Tests Done in Transmission for each Scintillator (All Uncertainties $\pm 5\%$)

Material	2 MeV	4 MeV	6 MeV	8 MeV
Chromox	75.5	216	393	728
PVT	51.9	80.3	174	256
CsI:Tl	0.812	2.32	3.15	4.75

Table 1 shows the measured yield-energy data accumulated during our tests. Tests were limited to 8 MeV due to proton penetration depth limitations. Uncertainties are dominated by current regulation instability on the order of $\pm 5\%$.
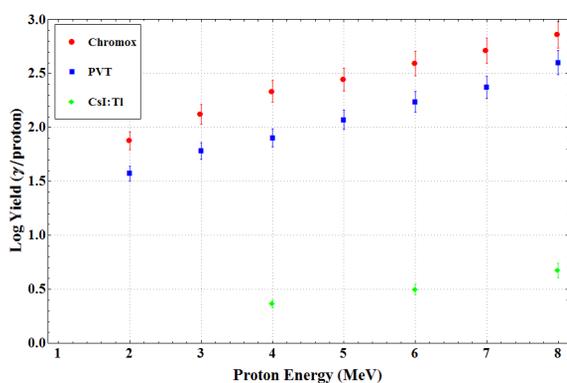

Figure 1: A comparison plot of $Log(Y(E))$ for each scintillator in transmission.

Chromox Transparency

Assuming a simple model of scintillation, light yield scales linearly with beam energy in absence of strong quenching. However, both Chromox and PVT yields do not correspond to a linear relationship. We consider the role of transparency in introducing nonlinearities in the yield. Chromox is constructed of granules of approximate size $w_g = 10 - 15\,\mu m$. Photons passing through the material may be scattered or reflected at each of the grain boundaries, such that the transmission coefficient through a granule is T_g. Assuming that $\frac{w_g}{w_c} \ll 1$ and $(1 - T_g) \ll 1$, we conclude that photon yield is a linear function of distance travelled through the material. Thus, we may use the range of protons in the scintillator, $r(E)$ as a linear transparency metric. We have

$$Y_A(E) = Y(E) * w_c(1 - r(E)) \qquad (2)$$

where Y_A is the transparency-adjusted yield. Figure 2 demonstrates that Y_A scales linearly with proton energy. We then work backwards to make an "expected yield" fit.
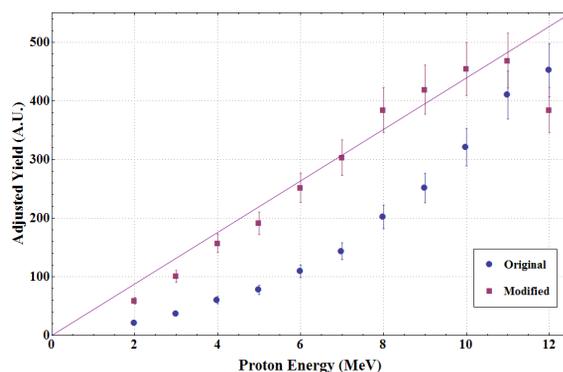

Figure 2: Chromox yield is shown with a penetration distance adjusment and corresponding linear fit. The raw yield is scaled down for comparison.

PVT Transparency and Damage

We performed a similar adjustment to the PVT yield, and after accounting for the Al coating, we achieve an improved fit. However, we observe a sharp discrepancy in the fit above 6 MeV. We believe this can be explained by nonradiative dissipation of deposited energy in the scintillator resulting in damage and a diminished yield for high incident flux [6]. To investigate, we placed the PVT under a continuous 8 MeV beam at 1 nA and examined the yield over time; we recorded a 31.6 % decline in mean intensity during 2 minutes of exposure. Afterwards, beam was blocked for 5 minutes, at which point the average yield was found to be consistent with the two minute value. As no significant afterglow was present, we conclude that there is a long term reduction in yield which corresponds to damage to the scintillator [9].

Resolution Analysis

For use in transmission, we performed comparative tests by imaging a pinhole with a 6 MeV CW beam. We imaged the output from each scintillator under these conditions, and the resulting images can be seen in figure 3. We then calculated the normalized intensity falloff from the edge of

the pinhole along a fixed vertical axis, averaged over 300 images.

These tests demonstrate a significantly lower scattering in CsI:Tl, leading to a 20% falloff length of 0.31mm. For Chromox, we found a 0.79 mm falloff length, while PVT displayed the greatest scattering with a falloff length of 1.15 mm. We also observe greater fluctuations in the scattering properties of the PVT than the Chromox, suggesting further evidence of damage to the scintillator.
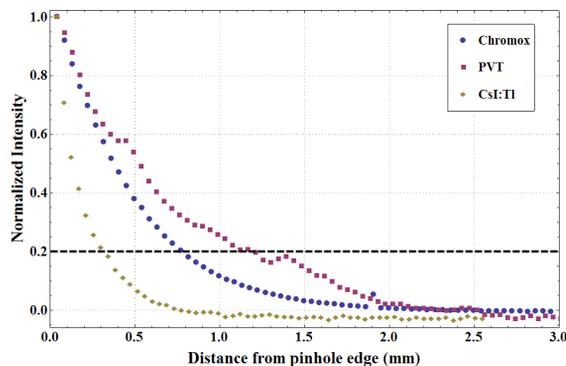

Figure 3: Intensity falloff from pinhole edge compared across three scintillator candidates.

Afterglow Analysis

Though boasting impressive scintillation response to ions and high $\frac{dE}{dx}$ particles, Chromox demonstrates an afterglow effect, only in part due to natural quenching. The granules introduces more lattice defects at grain boundaries, increasing the probability that photons are trapped away from an activator site thus enhancing afterglow. This effect has been measured in our Chromox sample both under continuous and pulsed beam conditions.

We generated a beam of 6 MeV protons at a current of 500 pA, and imaged the disc in reflection. The beam was shut off after an incidence period of several minutes, and the camera set to take pictures continuously at a 1 ms exposure time at approximately a 1 Hz rep rate. We found that there is significant afterglow for more than a minute after the beam is shut off. The sample exhibited a strong immediate afterglow, 28% of the value under beam exposure 1 s after beam shutoff. After 10 s, the afterglow intensity was less than 10% of the intensity under exposure. Even after 90 s, an afterglow of approximately 1.5% of the intensity under incidence was observed.

As laser acceleration produces sub-ns pulses, it is sensible to examine the afterglow under pulsed beam conditions as well. Though we cannot replicate experimental conditions with the tandem, pulsed beam was run at 3 Hz with 25 ms pulse lengths. A baseline response to the pulses was measured before blocking the beam to measure afterglow. Image intensity is plotted versus time in figure 4. It can be seen that in the case of pulsed beam, the light output falls much more quickly, reaching less than 3% of its nominal value after 0.1 s. Moreover, in this case, a stretched exponential of the form $e^{-(\frac{t}{\tau})^{\beta}}$ provides a strong fit candidate,

with $\tau = 0.18$ms, and $\beta = 0.20$. This fit is characteristic of phosphorescence and suggests that Chromox is suitable for pulsed use at Hz-scale rep. rates.
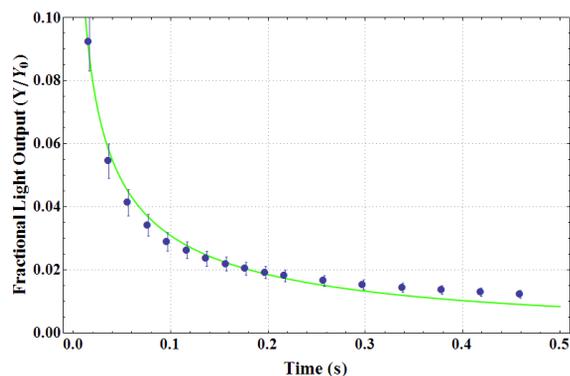

Figure 4: Chromox afterglow measured after a 5nA proton beam is pulsed for 25ms on, 325ms off.

CONCLUSION

We have measured the response of several candidate scintillators for use in a high rep rate laser acceleration experiment. Our findings suggest that Chromox has the strongest response to protons in the 2-10 MeV range. Resolution findings are worse than a single crystal scintillator like CsI:Tl, but acceptable for use with a Thomson spectrometer. Moreover, the afterglow in response to a pulsed beam is not significant on a 1s time scale, similar to the current maximum laser rep rate at ATF. Transparency remains a concern as it significantly reduces yield, depending on the geometry of the scintillator. Likewise, quenching remains a concern at high energies, but Chromox demonstrated the best radiation hardness among candidates. However, at low energies, photon scattering at grain boundaries reduces both yield and resolution for Chromox. Assuming comparable disc thickness, at energies < 4 MeV, a PVT based scintillator provides a superior response.

ACKNOWLEDGMENT

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