

SCINTILLATING SCREENS INVESTIGATIONS WITH PROTON BEAMS AT 30 keV AND 3 MeV

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Abstract

Luminescent screens hit by accelerated charged particle beams are commonly used as beam diagnostics to produce a visible emitted light, which can be sensed by a camera. In order to investigate the characteristics of the luminescence response of several scintillators, the beam shape and the observation of the transverse position, experiments were done with different low intensity proton beams produced by two different test benches.

This study is motivated by the need to identify scintillator materials for the development of a 4-dimensional emittance meter which will allow the characterization of the beams, in particular the emittance measurement (size, angular divergence).

This paper describes the experimental setups and our investigations of the optical properties of various scintillating materials at two different proton beam energies respectively about 30 keV and 3 MeV. The light produced by these screens is characterized by yield, flux of the emitted light versus the beam intensity, time response, and long life-time and they are compared.

INTRODUCTION

The characterization of the beams, in particular the emittance measurement (size, angular divergence) is a key point, both in the understanding of physical phenomena involved, such as space charge compensation, interaction with the residual gas, interaction with solid interfaces, or the dynamics of plasma ion sources, as in the validation of accelerators design.

As part of collaboration with the IPNO, a 4 Dimensions Emittance meter (EMIT4D) [1] is under development. It will provide, in a single measurement, the beam distribution in the transverse 4-dimensional phase space (X, X', Y, Y'), characterizing the beam with a high accuracy.

The principle of this instrument is simple. A screen drilled with 2D series of holes of very small diameter (called pepper-pot) intercepts the beam. It samples a grid of transverse beam positions. The particles passing through the holes will strike further a scintillator screen that emits light radiation. Physical properties of the original beam are reconstructed through the analysis of this radiation, collected by a dedicated video system (like a digital camera).

As part of this project, some measurements were done with several scintillators at two different proton beam energies respectively about 30 keV and 3 MeV in order to study the properties of each scintillator and determine

which one could be used with beam intensity from 0.1 μ A to 5 μ A and energy from few 10 keV up to few MeV.

SCINTILLATORS

The scintillators selection is based on the materials available and on use as diagnostics in proton beam production. Scintillation screens under study, like crystals, powder screens, and ceramics, are presented in Table 1. The "powder" scintillators have been provided by the CEA DAM except the BaF₂ provided by GSI. The thickness of the powder layer is also specified. Crystal scintillators YAG:Ce were bought at Crytur [2], BGO and Prelude 420 at St Gobain [3].

Table 1: List of Scintillators Under Study

Name Composition	Density g/cm ³	Light yield (photons/keV)	Thickness (mm)
P22 Y ₂ O ₂ S:Eu		45	0.008
P46 Y ₃ AlO ₁₂ :Ce ³⁺	4.5	6	0.008
P31 ZnS:Cu	4.09	130	0.01
BaF ₂	4.88	10	
BGO	7.13	8-10	0.25
YAG:Ce	4.5	16.7	0.25 & 1
Prelude420 Lu _{1.8} Y ₂ SiO ₅ :Ce	7.1	32	0.25
Al ₂ O ₃ :Cr	3.63	0.367	5

EXPERIENCE SETUPS

The measurements were done on two experimental setups at two different proton beam energies respectively about 30 keV and 3 MeV. The width of the beam spots was about 1 mm and the beam current was not higher than 5 μ A in both cases.

Low Energy Proton-Beam Production

The proton beam is produced by the ALISES 2 ion source developed at the CEA Saclay [4]. This ion source prototype delivers a pulsed beam of protons up to 34 mA at 40 keV of extraction energy. The extracted beam is transported to the diagnostic chamber, through the BETSI beam line [5] like shown Fig. 1.

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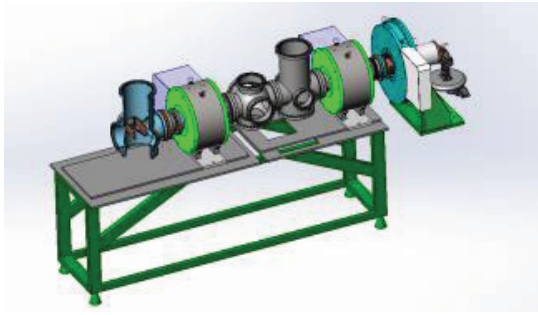


Figure 1: BETSI beam line with ALISES 2 ion source. The studied screens are installed at the end of the line (on the left) in the diagnostic chamber.

In the diagnostic chamber, a water-cooled cone shaped hole with an exit aperture of 1.1 mm was installed in front of the scintillator screen to reduce the beam intensity around $0.2 \mu\text{A}$. The scintillators are maintained on a linear translator in order to move the beam impact point on the surface. To measure the beam intensity at the screen position, a collector for ion beam current measurements was installed behind the scintillators. To reduce the secondary electron production that would increase the measured current value, the collector is equipped with a permanent magnet. The scintillator is positioned with a 50° angle to record the emitted light at the interaction point with a camera. The camera used is an Allied Vision GUPPY, connected in FireWire, synchronized with the ion source pulse and set to collect light during the machine pulse length. The camera is located outside the chamber at about 400 mm from the interaction point. Great care has been taken to be sure that the camera pixels do not get saturated while the emitted light is collected. The camera is controlled and recorded under LabView environment. The setup is presented in Fig. 2.

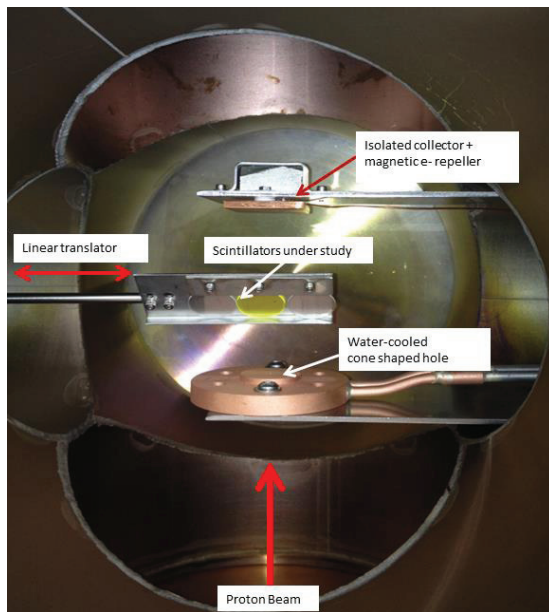


Figure 2: The diagnostic chamber, at BETSI, with the scintillators fixed onto a linear translator. In front of the scin-

tillator, a hole reduces the beam intensity. Behind, a collector is installed for ion beam current measurements. This picture is taken at the viewpoint of the camera.

3 MeV Energy Proton-Beam Production

The proton beam at 3 MeV is produced by a 3 MV Pelletron accelerator, Épipiméthée, equipped with an ECR multi-charged ion source. This accelerator, installed at CEA Saclay, is one of the accelerators of JANNUS facility [6]. On this machine, the current density can vary from 25 nA/cm^2 to few $\mu\text{A/cm}^2$ in a not-pulsed mode. To do the measurements with this 3 MeV energy proton beam, a setup similar to that of BETSI was installed at the accelerator Épipiméthée. A mechanical translator with the screen samples was mounted on a CF100 flange. To reduce the beam diameter, a diaphragm of about 2 mm was used and the current intensity was adjusted around $0.1 \mu\text{A}$. Several Faraday cups can be inserted to measure the beam intensity. The camera was installed on the chamber.

RESULTS

For each measurement presented in this report, the visible emitted light was obtained by integrating the light output in a region-of-interest chosen to be the central brightest region of the irradiated beam spot.

Light Emitted Intensities by Scintillators Under Study

Figure 3 presents the scintillation response of different scintillators as a function of number of irradiating protons. The beam energy is the same for all studies, about 35 keV. Beam current and pulse duration are different but, to allow the comparison of scintillation yield and degradation, each measurement was converted in number of protons. The powder scintillators P22, P31 and P46 produced the highest visible emitted light. Concerning the BaF_2 scintillator, we have to increase the camera aperture about 128 times to detect its visible emitted light. Indeed, its wavelength of maximal emission is in UV spectrum while the used camera detects only the light emitted in the visible spectrum.

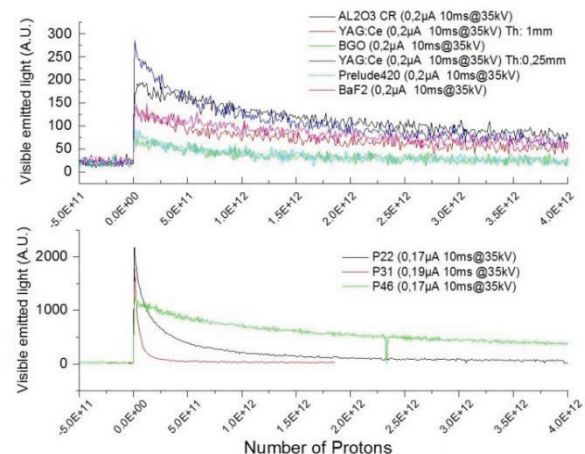


Figure 3: Visible emitted light from studied scintillator screens as a function of protons particles number at beam energy of 35 keV.

Figure 3 shows a fast degradation of scintillation for powder scintillators P22 and P31. The scintillators which have the lowest degradation are the scintillators P46, YAG:Ce and $Al_2O_3:Cr$.

The composition of the powder scintillator P46 is close to a YAG:Ce scintillator. Figure 4 shows a comparison between the YAG:Ce materials with different thickness. It seems that the light is higher with a smaller thickness.

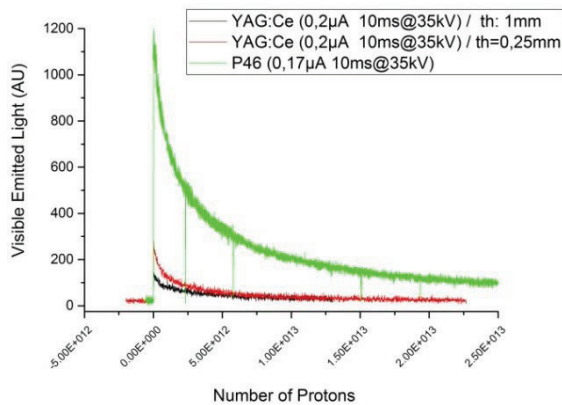


Figure 4: Visible emitted light from YAG:Ce and P46 scintillators as a function of protons particles number at beam energy of 35 keV.

Influence of the Pulse Length

The time collection of the camera has been increased in order to collect the light emitted during the pulse time of 20 ms. In Fig. 5, the visible emitted light was normalized to show that the scintillation yield degradation of this intensity follows the same decay with two different pulse lengths (10 ms and 20 ms). We also noted that the emitted light intensity is twice as high as for the 20 ms pulse length.

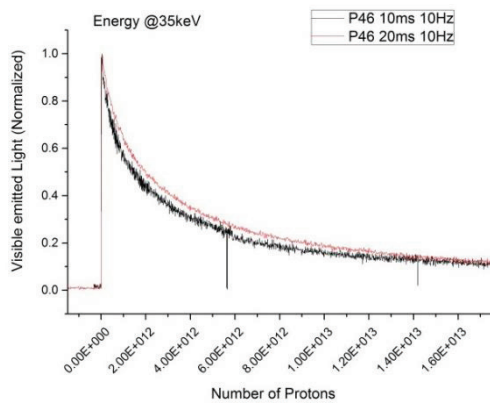


Figure 5: Normalized light output of scintillator P46 vs number of particles with different pulse lengths

Influence of the Pulse Repetition Rate

To check if the thermal heat up due to particle implantation plays a crucial part on the scintillation yield degradation, two measurements at two different repetition rates, 4 and 10 Hz, with the same beam intensity, were done. Results are presented in Fig. 6. In spite of a difference of

power deposition, estimated from 0.24 to 0.6 mW, no influence of the repetition rate on the light output amplitude and scintillation yield degradation can be observed.

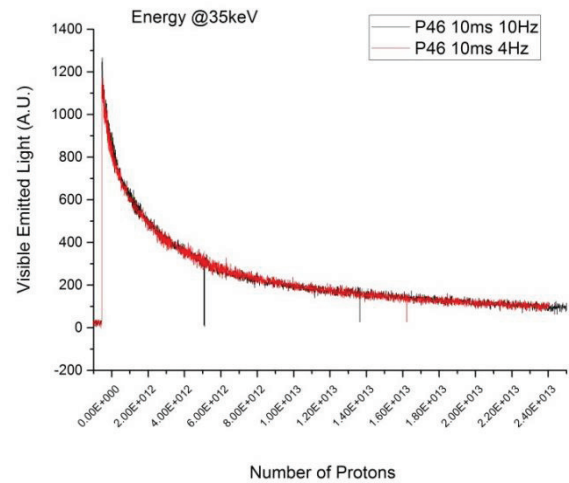


Figure 6: Light yield of scintillator P46 vs number of particles with different repetition rate.

Influence of Energy

To check the influence of energy on the scintillation yield degradation, several measurements were done at different energies from 35 keV to 3 MeV. Figure 3 shows that the materials YAG:Ce, P46 and Al_2O_3 have the slowest light output degradation. Those scintillators were, therefore, chosen to be studied at energy of 3 MeV.

First measurements showed that the Al_2O_3 had an important remanence and caused major breakdowns. This scintillator has been set aside.

In Fig. 7, the visible emitted light was normalized to compare the behaviour of scintillator P46 at two different energies, 35 keV and 3 MeV. The light output is much less degraded at 3 MeV. This observation was also reported in some studies on other scintillators [7].

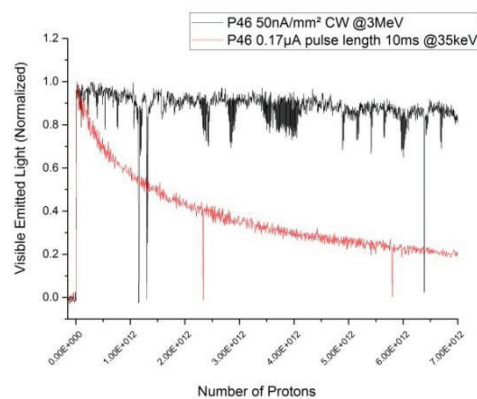


Figure 7: Light yield of P46 scintillator as a function of number of protons irradiated at beam energies of 35 keV and 3 MeV

In Fig. 8, a test was carried out with the YAG:Ce at 3 MeV and with beam density of 100 nA/mm². To understand if the degradation is irreversible, the irradiation was stopped for several minutes. The amplitude of light output

resumes at the same amplitude. Degradation is therefore irreversible. When the bombarding of protons number is high, even at 3 MeV we observe a notable degradation.

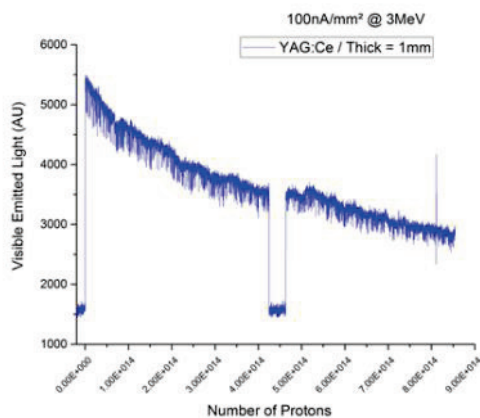


Figure 8: Visible Emitted light from YAG:Ce as a function of protons particles number irradiated by protons at beam energy of 3 MeV with a beam interruption done during the measurement.

DISCUSSION

A theoretical calculation to determine the beam penetration in scintillator P46 can be done. The stopping power for protons is given by [8], with the density of P46, beam penetration at 35 keV can be calculated around 21 nm and at 3 MeV around 24 μm . At low energy, the power is concentrated on a very small volume, which could explain the degradation.

The luminescence of a scintillator is due to the presence of defects and impurities producing local energy levels in the region called “forbidden band” between the conduction and valence bands. The incoming low energy particle have three kinds of interaction on the material: activators in which the photo-emission accompanies the transition of an electron of the material to the ground state, defects in which the energy is only dissipated by thermal effect and excitons in which electrons may return to the valence band or to the conduction band without emission of photon. The photoemission results in an interaction between the transition process of an electron from the conduction band to the valence band and thermal dissipation processes. Birks [9] states that the exponential decay of the luminescence production efficiency observed vs the bombardment time by low energy incident ions is due to the absorption of photons by damaged sites.

CONCLUSION

Several scintillators were investigated under proton radiation with variable beam conditions. At low energy, the visible emitted light for all scintillators shows degradation. This degradation depends on the number of protons. Even at 3 MeV, this degradation is present with an important number of protons. More investigations can be done to find a material with a limited degradation but for the moment, the P46 material seems to be the most suitable scintillator for our EMIT4D. This scintillator has the slowest light output degradation as compared to the other materials and a high light yield.

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REFERENCES

- [1] A. Dumancic *et al.*, “EMIT4D,” *Journées Accélérateurs 2015*, Roscoff, Paris, France.
https://www.researchgate.net/publication/306056164_4D_emittancemeter?channel=doi&linkId=57ac8ae908ae0932c9748f5a&showFulltext=true
- [2] <http://www.crytur.com/>.
- [3] <http://www.crystals.saint-gobain.com/>.
- [4] O. Delferrière *et al.*, “Advanced Light Ion Source Extraction System for a New Electron Cyclotron Resonance Ion Source Geometry at Saclay,” *Rev. Sci. Instrum.*, 83. doi:10.1063/1.3660820
- [5] O. Tuske *et al.*, “BETSI, a new test bench for ion sources optimization at CEA SACLAY,” *Rev. Sci. Instrum.*, Feb2088, Vol. 79, Issue 2, p02B710.
<http://jannus.in2p3.fr/spip.php>
- [7] L.Y. Lin *et al.*, “Study of Scintillation Stability in KBr, YAG:Ce, CaF₂:Eu and CSI:TI Irradiated by Various-Energy Protons,” *IBIC2014*, Monterrey, CA, USA
- [8] http://physics.nist.gov/cgi-bin/Star/ap_table.pl
- [9] J.B. Birks. “Theory and Practice of Scintillation counting,” *Pergamon press New York* (1964), USA.