SCINTILLATION AND OTR SCREEN CHARACTERIZATION WITH A 440 GeV/c PROTON BEAM IN AIR AT THE CERN HIRADMAT FACILITY

S. Burger†, B. Biskup[1], S.Mazzoni, M.Turner[2], CERN, Geneva, Switzerland
[1]also at Czech Technical University, Prague, Czech Republic
[2]also at Graz University of Technology Theoretical Physics Institute, Vienna, Austria

Abstract

Beam observation systems, based on charged particles passing through a light emitting screen, are widely used and often crucial for the operation of particle accelerators as well as experimental beamlines. The AWAKE [1] experiment, currently under construction at CERN, requires a detailed understanding of screen sensitivity and the associated accuracy of the beam size measurement. We present the measurement of relative light yield and screen resolution of seven different materials (Chromox, YAG, Alumina, Titanium, Aluminium, Aluminium and Silver coated Silicon). The Chromox and YAG samples were additionally measured with different thicknesses. The measurements were performed at the CERN's HiRadMat [2] test facility with 440 GeV/c protons, a beam similar to the one foreseen for AWAKE. The experiment was performed in an air environment.

INTRODUCTION

The accelerators at CERN use more than 250 beam instruments based on scintillation and/or Optical Transition Radiation (OTR) screens. Even though the emission of scintillation and OTR light is very well understood, comparative measurements of commonly used screen types are hard to find.

We tested 13 typical screen materials (see Table 1 and Fig. 1) in the HiRadMat [2] test facility. We used a 440 GeV/c proton bunch from the CERN SPS populated with 10^{11} protons with a radial proton beam size of $\sigma = 2$ mm.

EXPERIMENTAL SETUP

Layout

Figure 2 shows a 3D model of the experimental setup. A linear stage with a stepper motor is used to select screens. The screens are positioned at 45 degrees with respect to the incoming beam. A mirror reflects the light emitted by the screens to a CCD camera (WATEC 902H3) equipped with a 25 mm focal length camera lens. This optical line gives calibration values of ~100µm/pixel in both the horizontal and vertical planes.

Two rotatable optical filter wheels are placed in front of the camera lens to, if necessary, reduce the light transmission from 100% down to 0.00001% in 14 steps.

A second linear translation stage is available to move an aluminium foil of 100µm thickness in front of the screen to prevent any light created upstream from reaching the camera. Additionally, we surrounded the setup with a blackened metal box that has two openings for the entrance and exit of the beam. The presence of a beam dump located approximately 10 meters downstream our setup resulted in an elevated background noise on the camera image due to backscattering.

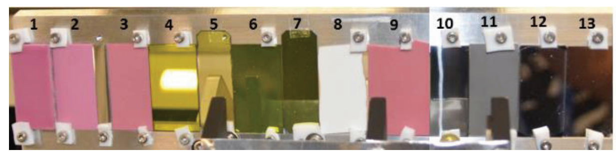

Figure 1: Image of the screen material samples mounted on the screen holder.

Table 1: Material Samples Shown in Figure 1

Screen Nr.	Material	Thickness [mm]	Supplier
1	Chromox ($Al_2O_3:CrO_2$)	3.0	*CeraQUest*
2	Chromox ($Al_2O_3:CrO_2$)	1.0	*CeraQuest*
3	Chromox ($Al_2O_3:CrO_2$)	0.5	*CERN stock*
4	YAG (YAG:Ce)	0.5	*Crytur*
5	YAG (YAG:Ce)	0.1	*Crytur*
6	YAG back-coated (YAG:Ce + Al)	0.5	*Crytur*
7	YAG back-coated (YAG:Ce + Al)	0.1	*Crytur*
8	Alumina (99% purity)	1.0	*GoodFellow*
9	Chromox-old type ($Al_2O_3:CrO_2$)	1.0	*CERN stock*
10	Aluminium	1.0	*CERN stock*
11	Titanium	0.1	*GoodFellow*
12	Aluminium coated Silicon	0.25	*MicroFabSolutions*
13	Silver coated Silicon	0.3	*Sil'Tronix*

Control and Acquisition

The measurement setup is controlled via VME based modules. The control of the filter wheels, light for calibration and the image acquisition are made through the standard CERN beam observation electronics [3].

We used an analogue camera that is not synchronized with the proton beam. The camera triggers every 20ms and integrates over a 20ms period. The acquisition is performed by capturing the image in the acquisition board on ever vertical sync. from the video signal (i.e. each 20ms).

† stephane.burger@cern.ch

ISBN 978-3-95450-177-9

A timing signal linked to the extraction of the beam from the SPS triggers the image to be stored as a beam measurement.

Since there is no synchronisation between the camera and the extraction timing of the CERN SPS, there is an uncertainty of up to 20ms between when the proton beam arrives and when the frame from the camera is captured. This does not affect the light yield of OTR screens as the light emission is instantaneous during the passage of the proton bunch. As the proton bunch length is only a few ns, much shorter than the camera exposure time, we can safely assume that all light is captured in a single frame. Capturing scintillation light is, however, different. The light emitted follows an exponentially decaying profile with a decay constant that depends on the screen material and can reach up to tens of milliseconds. As such, depending on when the proton beam hits the screen with respect to the camera trigger, a different fraction of the emitted light is integrated in a single camera frame. In order to cope with this effect, we rejected all measurements that had a significantly lower light yield than the maximum measured for each screen, keeping approximately 70% of the recorded images. Using a camera synchronised to the extraction timing of the CERN SPS beam would solve this problem.

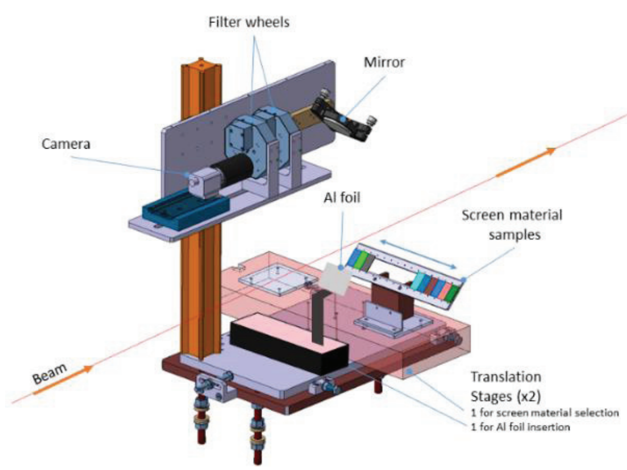

Figure 2: Experimental setup of the screen test.

THEORETICAL ASPECT

Light Emission in Air

When a charged particle beam propagates in air instead of the usual high vacuum of accelerator beam pipes, several parasitic light emitting processes can contribute to the signal measured by the camera:

1) Forward OTR photons are generated by the interaction of the protons with the vacuum pipe exit window. However, in our case the contribution from this can be considered as negligible, as the vacuum window is 1.94m upstream of the measurement.
2) Cherenkov and luminescence photons are generated all along the 1.94 m path in air from the vacuum exit window up to the measurement station.

These two processes are considered as parasitic light that add, by reflection on the screen, to the scintillating or OTR light generated by the screen itself. The higher the reflectivity of the screen, the more parasitic light contributes. We tried to supress this effect by inserting an opaque foil 43 mm in front of the light emitting screen (see Fig. 3). However, such a foil is a source of (forward) OTR for the measurement screen that has to be accounted for. When measuring OTR screens, the forward OTR produced by the foil interferes with the backwards OTR produced by the screen under test. The total light yield and angular distribution depends critically on the energy of the beam, the radiation wavelength and the distance between the two radiators [4, 5]. In the present case, the so-called formation length defined as $l_f = \gamma^2\lambda/2\pi$ is 1.75 cm at a central wavelength of 500 nm, so that the total light yield emitted by the two screens is approximately twice that of a single screen.

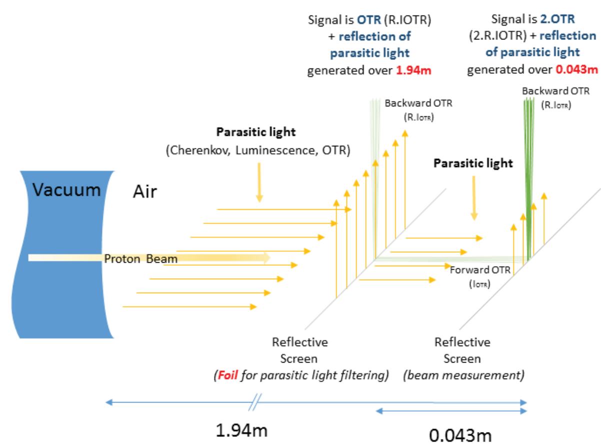

Figure 3: Layout of the different light emission processes included in the screen measurements. The foil inserted before the beam screen blocks the parasitic light generated upstream in the air but itself generates forward OTR that reached the measurement screen.

The expected scintillation light yield is not straightforward to calculate, and so was only measured.

Cherenkov

Protons in air produce Cherenkov photons with an angular distribution of θ [6]:

$$\theta(E) = \cos^{-1}\left(\frac{1}{\beta(E).ng(P)}\right) \quad (1)$$

where βis the beam relative velocity and *ng* is the index of refraction of air.

The number of generated photons N_{ch} was calculated as:

$$N_{ch} = 2\alpha.\pi.L.\left(\frac{1}{\lambda a} - \frac{1}{\lambda b}\right).\sin\left(\theta(E)\right)^2 \quad (2)$$

where α is the fine structure constant, *L* is the length of the air channel where the light is generated and λ_a-λ_b is the spectral bandwidth.

ISBN 978-3-95450-177-9

Luminescence

The number of photons N_{sc} created by luminescence in air (in 4π) was estimated as [7]:

$$N_{sc}(L,\alpha) = \frac{\rho.Na}{M}.\left(\frac{Pe}{Pi}\right).\sigma_{sc}.L \quad (3)$$

where ρ is the air density, Na is the Avogadro constant, M the molar mass of air, Pe/Pi is the ratio of the air pressure to the atmospheric pressure, σ_{SC} is the scintillation cross section and L is the length of the air channel where the light is generated.

OTR

The OTR light process on the measurement screen generates photons following the expression [6]:

$$N_{OTR}(E) = 2.R.\frac{2\alpha}{\pi}.\ln\left(\frac{\lambda b}{\lambda a}\right).\left(\ln\left(2\gamma(E)\right) - \frac{1}{2}\right) \quad (4)$$

where R is the screen reflectivity and γ is the Lorentz factor.

As results of Eqs.(1, 2, 3 and 4), the calculated light yields for all processes are presented in Table 2, taking into account the acceptance of the optical system.

Table 2: Expected Light Yields from OTR Screens and Expected Contributions from Parasitic Light for no Blocking Foil and with Blocking Foil Inserted

	Without Foil	With Foil
Path length of protons in air	1.94 [m]	0.043 [m]
Number of photons	N	N_f
N_{OTR} (protons on screen)	2.98E-2	2.98E-2
N_{Ch} (protons in air)	4.266	1.132
N_{Lu} (protons in air)	6.60E-2	1.23E-04
Total	$N_{OTR}+N_{Ch}+N_{Lu}$	$2xN_{OTR}+Nf_{Ch}+Nf_{Lu}$
Ntotal	4.36E+00	1.19E+00
N/Nf	3.66E+00	

For both cases (without and with foil), the Cherenkov light contributes with 2 orders of magnitude more photons than OTR or Luminescence.

This means that for highly reflective OTR screens (Ag coated Si, Al coated Si), the main contribution of parasitic light to our measurement comes from photons produced by Cherenkov radiation. Inserting the blocking foil reduces this contribution by a factor of four.

The contribution of parasitic signal in the case of a scintillating screen cannot be easily calculated, as the light yield of the screen is a priori not known. However, due to the higher photon yield of scintillation and the lower optical reflectivity of the surfaces, we expect it to be less important than in the OTR case.

MEASUREMENTS AND RESULTS

Systematic Measurements

Some 10 to 25 measurements per screen were obtained, with the majority taken with the light blocking foil inserted. The optical filters were carefully chosen to avoid image saturation. Figure 4 shows a typical measurement with (right) and without (left) the blocking foil. The parasitic light suppression by the foil is clearly visible.

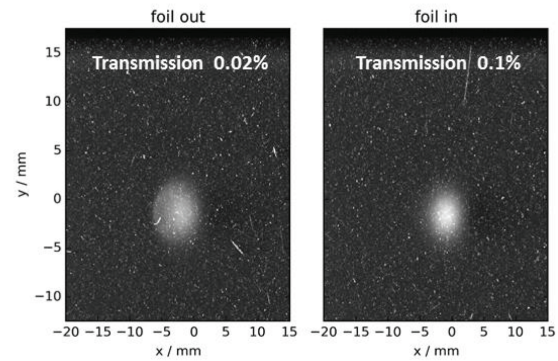

Figure 4: Example of raw images of the proton beam in air on a Silver coated Si OTR screen without (left) and with (right) blocking foil in place. The change of intensity as well as beam size is clearly visible.

Analysis Process

After subtracting the background, the pixels are integrated over the vertical axis, resulting in an integrated horizontal profile. We normalized the image with respect to the beam intensity and choice of filter. The data shown in Figs. 5 and 6 represent the mean (marker) and standard deviation (error bar) of each pixel column. Finally, a Gaussian fit is performed, which gives the relative yield and measured beam sigma.

Results

Figures 4 and 5 show that the main differences between blocking foil in and out are the lower light yield and reduced sigma of the Gaussian fit. Additionally the centre of the Gaussian shifts for the silver coated silicon and alumina screens. We explain this difference in yield and sigma by the contribution of the parasitic light, which is considerably reduced with the blocking foil in as mentioned in the previous section. In the case of Silver coated Silicon (top plot of Fig. 5), the light yield with blocking foil inserted is 6.6 times less than without the foil. In the case of scintillator screens (middle and bottom plots), this difference is lower than expected. The shift of the centre of the Gaussian is not yet understood, but we suspect this to be due to a change in the reflectivity and/or the diffusivity of the material combined with errors in the alignment of the optical line.

ISBN 978-3-95450-177-9

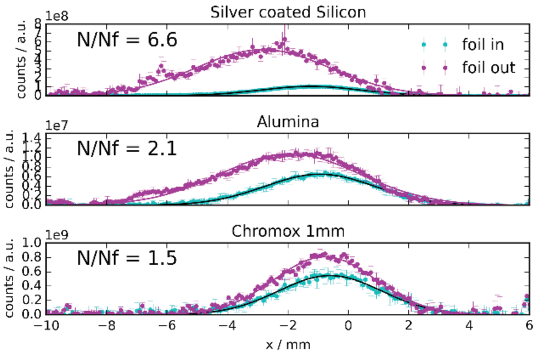

Figure 5: Results of the beam profile measurement showing the response of the silver coated silicon, Alumina and Chromox screens with and without blocking foil.

Figure 6 shows the measurement of all screens with the light blocking foil inserted. Based on this data, Tables 3 and 4 give the relative yield and relative sigma obtained from the Gaussian fit for all screen materials.

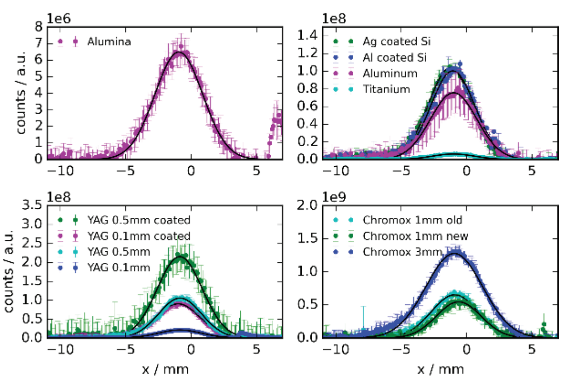

Figure 6: Results of beam profile measurements showing the response of all screens listed in table 1 with a foil blocking the parasitic light installed 43mm upstream.

Table 3: Light Yield Measured on each Screen with a Foil Positioned 43mm Upstream to Block Part of the Parasitic Light. The Values are Referenced to a 1mm Thick Chromox Screen as it is Commonly Used in Many of the CERN Beam Observation Systems

	Type	Yield [%]	Error [%]
$Al_2O_3:CrO_2$ 3mm	Scint.	232.73	2.34
Chromox 1mm (old type)	Scint.	118.18	3.08
$Al_2O_3:CrO_2$ 1mm	Scint.	100	3.64
YAG:Ce 0.5mm + Al back Coated	Scint.	40.00	4.55
YAG:Ce 0.5mm	Scint.	19.27	4.72
Si + Ag coated	OTR	18.91	3.85
Si + Al coated	OTR	18.18	4.00
YAG:Ce 0.1mm + Al back Coated	Scint.	15.45	35.25
Aluminium 1mm	OTR	14.55	25.00
YAG:Ce 0.1mm	Scint.	3.87	3.29
Alumina (99%) 1mm	Scint.	1.20	7.58
Titanium 0.1mm	OTR	1.13	9.68

As expected, the 3 mm thick Chromox screen gives both the highest yield and the largest beam size due to its thickness. Due to their high reflectivity the OTR screens (except for titanium) have a yield only a few times lower than scintillating material, which for comparison is 3 orders of magnitude difference in vacuum, due to the contribution of reflected parasitic Cherenkov light generated upstream. The best resolution was obtained by the Titanium screen, probably due to its diffusive aspect and low reflectivity. Titanium additionally has the lowest light yield.

Table 4: Sigma measured on each screen with a foil positioned at 43mm upstream to block part of the parasitic light. The values are referenced to the Titanium screen as it gives the smallest sigma value of 1.61mm

	Type	Sigma diff. with ref. Ti screen [%]	Error [%]
Titanium 0.1mm	OTR	0	2
YAG:Ce 0.5mm	Scint.	+1.86	6
YAG:Ce 0.1mm	Scint.	+2.48	5
Si + Ag coated	OTR	+2.48	4
Si + Al coated	OTR	+4.35	4
YAG:Ce 0.5mm + Al back Coated	Scint	+5.59	10
Chromox 1mm	Scint	+5.59	10
Aluminium 1mm	OTR	+8.07	7
Chromox 1mm (old type)	Scint	+11.18	6
YAG:Ce 0.1mm + Al back Coated	Scint.	+11.80	50
Alumina (99%)	Scint.	+12.42	7
Chromox 3mm	Scint	+34.78	7

CONCLUSION

The light emission from a proton beam of 440 Gev/c in air was measured for three scintillators (Alumina, Chromox and YAG) of different thicknesses and four OTR emitting screens (Ag coated Si, Al coated Si, Ti and Al). A light blocking foil was inserted to reduce the contribution of parasitic light created upstream of the target material. Nevertheless, the majority of the photons observed due to Cherenkov light generated as the relativistic proton beam passes through the air in front of the screen. The conclusion is therefore that no precise OTR vs scintillator light yield and subsequent resolution studies can be performed with this data. Future studies under vacuum are thus foreseen to better asses these questions. However, these set of measurements represent an extremely useful reference for setting up a beam imaging system in air.

ACKNOWLEDGEMENT

The authors want to thank E. Bravin and T. Lefevre for all fruitful discussions that helped in the understanding of this screen study. Also, the contribution of J. J. Gras on the data logging was very much appreciated. The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project EUCARD-2, grant agreement no. 312453””

ISBN 978-3-95450-177-9

REFERENCES

[1] E. Gschwendtner *et al.*, "AWAKE, The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN", NIMA DOI: 10.1016/j.nima.2016.02.026.

[2] I. Efthymiopoulos *et al.*, "HiRadMat: A new irradiation facility for material testing at CERN", Proceedings of IPAC 2011, San Sebastian, Spain.

[3] S. Burger and E. Bravin, "A new Control System for the CERN TV Beams Observation", CERN-AB-Note-2008-041-BI.

[4] Wartski *et al.*, "Interference phenomenon in optical transition radiation and its application to particle beam diagnostics and multiplescattering measurements", J. Appl. Phys. 46, 3644 (1975).

[5] M. Bergamaschi *et al.*, "Optical Transition Radiation interference in the near and far-field regions", manuscript in preparation.

[6] Jackson J. D. "Classical Electrodynamics", Wiley 1999.

[7] Bosser *et al.*, "N2 and Xe Gas Scintillation Cross-Section, Spectrum, and Lifetime Measurements from 50 MeV to 26 GeV at the CERN PS and Booster", Nucl. Instrum. Methods Phys. Res., A 492 (2002) 74-90.

ISBN 978-3-95450-177-9