SINGLE PASS OPTICAL PROFILE MONITORING

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Abstract

Beam profiles are acquired in transfer lines to monitor extracted beams and compute their emittance. Measurements performed on the first revolutions of a ring will evaluate the matching of a chain of accelerators. Depending on the particle type and energy, these measurements are in general performed with screens, making either use of Luminescence or Optical Transition Radiation [OTR], and the generated beam images are acquired with sensors of various types. Sometimes the beam position is also measured this way. The principle, advantages and disadvantages of both families of screens will be discussed in relation with the detectors used. Test results with beam and a possible evaluation method for luminescent screens will be presented. Finally other optical methods used will be mentioned for completeness.

SCREEN MONITORS

Screen monitors are the most popular instruments for single pass profile measurements. A typical monitor is depicted in Fig. 1. It consists of a vacuum vessel with Input and Exit ports for the beam, a mechanism holding several screens, 2 or 3 are usual numbers, a window to extract the light produced by the screen, an optical set-up to image the screen onto a sensor and to control the quantity of light transmitted, and finally a detector to convert the photons into an electrical signal, be it a TV standard signal or a digital acquisition.

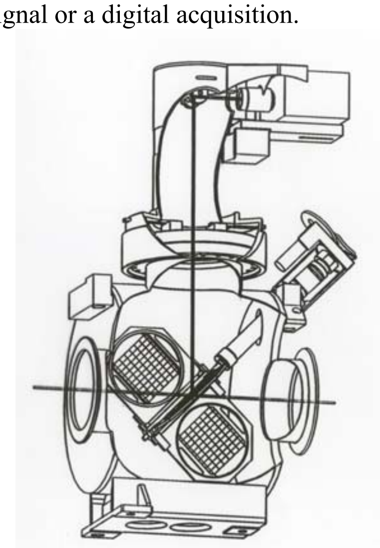

Figure 1: Typical screen monitor.

In the following, we shall revue the various types of screens and mention the most important features of the sensors for this type of monitor. The match of these two constituents will largely define the performance of the monitor.

SCREENS

Two types of screens are in general use: Luminescent screens and Optical Transition Radiation [OTR] screens. The first produce light by excitation of the molecules of the screen by the passage of a charged particle beam followed by de-excitation, which is a bulk phenomenon, whereas the second produce light by an electromagnetic phenomenon initiated by the passage of the beam at the interface of two regions with different dielectric constants, and is hence a pure surface phenomenon.

Luminescent screens

When a molecule is excited by an external electromagnetic field, it can emit light via two processes. The first is characterised by a direct jump to the base level with a short decay time constant of a few tens of nanoseconds and will be called fluorescence. In the second process, the de-excitation passes via an intermediate receiver level and takes much longer, typically microseconds to seconds. It will be called phosphorescence. If both processes are present, which is the case with many screens, or in case of doubt, the light emission will be called luminescence.

A first screen type is manufactured from ceramics or glass in which activators have been introduced for controlling the emitted wavelength. The most popular dopant for ceramics is Cr, which results in an emission in the red, well matched to solid-state detectors: see Fig. 8. The concentration of activator, of a few per mil, controls the emitted intensity. Typically, such screens are made from Al_2O_3 powder, with grains of the order of 5 μm, to which silica magnesia lime and the activator, here Cr_2O_3, are added to arrive at a concentration of 99.4% of Al_2O_3. This powder is mixed and pressed, before being fired to sinter, process in which the glassy phase fills up the voids between the grains. After machining to the final shape and finish, typically to Ra~1μm, there is another firing. Microscope observations show large structures, up to ~30μm, in the finished product.

Another type of screen uses crystalline materials, where dopants also control the emitted wavelength. These screens are in general more expensive, but as will be seen later, have a better resolution as well as a higher light yield, i.e. sensitivity. There is experience with two types: Thallium doped CsI [1] and Cerium doped YAG [2].

As the light is generated in the bulk of the material, if the screens are placed at 45° with respect to the beam and if they are not infinitely thin or made of opaque material, there will be a collection of light generated in the depth of the material which will create instrument generated tails [3], in the vertical direction in the case of the Fig.1 set-up. To counteract this degradation, monitors have been built [4] with the luminescent screen perpendicular to the beam direction and with a light extraction mirror placed at 45° with respect to the screen and the beam direction: Fig. 2. As will be seen later, the mirror will generate OTR, which will add to the luminescence signal, but the generated light levels are sufficiently different so that OTR can be neglected: see Table 1.

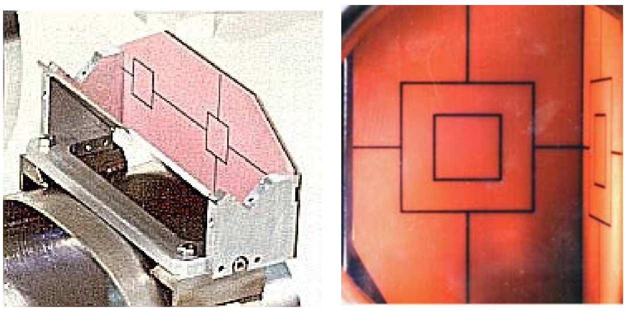

Figure 2: Monitor set-up with perpendicular screen and 45° extraction mirror, with screen at right and mirror at left. Left : actual set-up, right: as seen by the camera.

A recent revival of an old technique where a phosphor layer is put on a metal sheet or a glass substrate [5,6] will also solve this problem. Phosphors of type P40 and P43, the latter with a thickness of 40µm and a grain size of 5µm, have been used. The main disadvantage of these screens is the mechanical fragility of the phosphor layer.

OTR screens

Optical Transition Radiation makes use of the radiation emitted when a charged particle beam goes through the interface of two media with different dielectric constants, like vacuum and a metal sheet. Two light patterns are emitted, see Fig. 3.

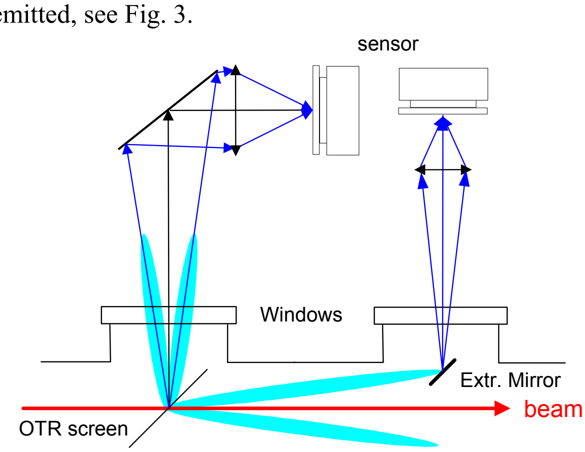

Figure 3: OTR screen monitor, with backward and forward OTR patterns and their imaging schemes.

The most popular use of OTR is for backward production, where the screen produces light in the specular direction. In this case, the image quality depends on the surface flatness of the screen. The photon production between two wavelengths λ_1 and λ_2, at an angle θ with respect to the specular direction, is given by:

$$\frac{dN}{d\theta} = \left[\frac{\alpha}{2\pi} R^2 L_N \frac{\lambda_2}{\lambda_1}\right] \frac{1}{\theta} \frac{1}{\left(1+1/(\theta\gamma)^2\right)^2}$$

where γ is the Lorentz energy factor, α the fine structure constant and R the reflection coefficient of the screen. The resulting angular distribution of photons between 450 and 750nm is given in Fig. 4 for a 450 GeV proton.

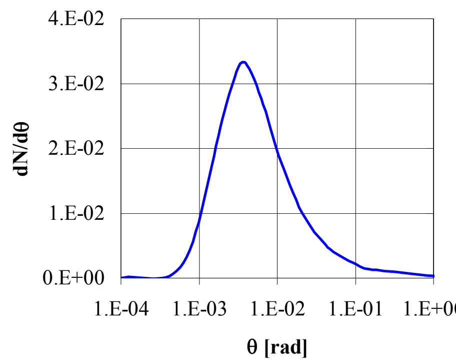

Figure 4: backward OTR photon production between 450 and 750nm for a 450 GeV proton.

The distribution has a central hole and a peak located at $1/\gamma$. For quite some time, this pattern was considered to limit the usefulness of OTR monitors to low γ beams because of diffraction until it was demonstrated analytically [7] and experimentally [8,9] that this was not the case, because most of the emission is spread over the long tail.

For the forward OTR, the light from part of the pattern is extracted at a finite angle, to avoid the particle beam. This type of monitor has to our knowledge only been used at CEBAF [8] with 250nm thick Carbon screens, placed perpendicularly to the beam. Its main advantage is to be independent of the surface flatness of the screen, which allows the use of very thin screens. A quantity that is often quoted in this case is the formation length, given by the formula:

$$l_f = \frac{2\lambda/2\pi}{\theta^2 + 1/\gamma^2}$$

This formation length is small for protons, but can go to large distances, hundreds of metres, for leptons, which was supposed to limit its use. It is accepted that this formation length is irrelevant for imaging applications.

Screen Performance and Test results

Several measurements can be performed to assess the performance of a screen. These measurements are in principle to be made with the beams on which the screen will be used.

The first measurement is that of the screen sensitivity. To compare various materials, it is possible to use a monitor of the type depicted in Fig.1 having a screen holder fitted with different screen types: Fig. 5.

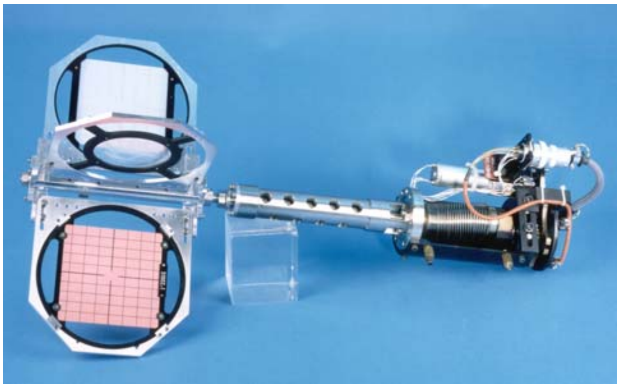

Figure 5: Screen holder with 3 screens (from bottom to top: Al_2O_3[Cr], CsI[Tl], Quartz) and one empty position for the free passage of beam.

The results of the measurements obtained with protons in the CERN SPS complex are given in Table 1. It can be seen that the studied screens cover a large dynamic range of 3 10^6. Due to the OTR emission pattern, the sensitivities could be slightly improved with leptons.

Table 1: Screen Sensitivities measured with protons and normalized for images with 7 pixels per beam sigma

Type	**Material**	**Activator**	**Sensitivity** [p]
Luminesc.	CsI	Tl	6 10^5
"	Al_2O_3	0.5%Cr	3 10^7
"	Glass	Ce	3 10^9
"	Quartz	none	6 10^9
OTR	Al		2 10^{10}
"	Ti		2 10^{11}
"	C		2 10^{12}

Another important parameter for luminescent screens is the emission spectrum. This test can in principle be done with any beam able to excite the luminescence. Given in Fig. 6 are the spectra for different screens, measured with 450 GeV protons in the SPS extraction lines.
The measurement of the duration of the light emission can be performed at the same time for the luminescent screens. This parameter depends on the activator and probably on its concentration. The results are summarised in Table 2. The decay time for YAG[Ce] screens is given to be around 100ns and that of P43 to be equal to 1ms [6]. OTR screens have been able to provide measurements of bunch lengths down to picoseconds [12].
If the screens are under vacuum as in Fig.1, it is difficult to explore the characteristics of many screens in a reasonable time, because of the vacuum interventions. It is easier in this case to use a set-up as developed at ESRF where the screen is in air in a thin-walled tube that can be inserted in the beam line [3]. This could allow testing as many screen types as needed with a minimum of interventions.

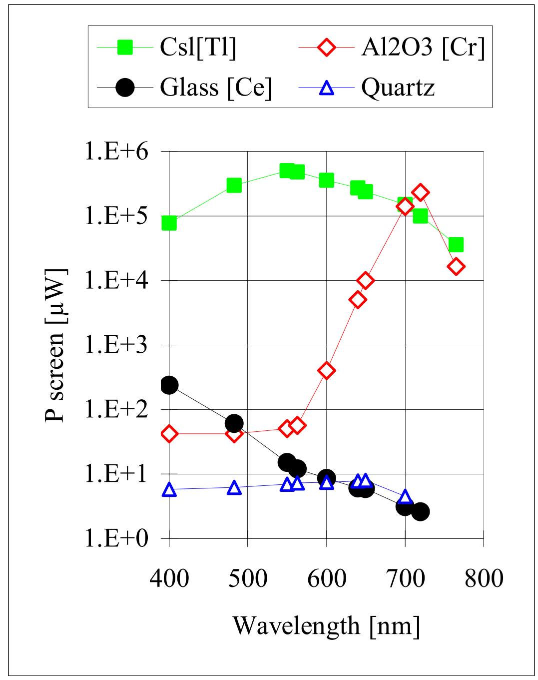

Figure 6: Emission spectra of various luminescent screens normalised for 10^{13} protons at 450 GeV.

Table 2: Decay times of luminescent screens

Screen	**Activator**	**Decay time constant**
Al_2O_3	Cr	>20ms
CsI	Tl	900ns
Glass	Ce	100ns
Quartz	None	ns

Whatever the set-up, some measurements are difficult or even impossible to perform with particle beams. This is for instance the case for resolution assessments. So another set-up, independent of an accelerator beam was looked for. An obvious candidate was a laser beam.

Table 3: Comparative Sensitivity Measurements for luminescent screens

Screen	**Activator**	**Sensitivity**		
		p beam		**UV laser**
		Abs.	Rel.	relative
CsI	Tl	6 10^5	10^4	10^4
P43	Tb			3 10^3
YAG	Ce			4 10^2
Al_2O_3	0.5% Cr	3 10^7	2 10^2	3 10^2
Glass	Ce	3 10^9	2	
Quartz	none	6 10^9	1	1

Tests were performed with an available UV laser (180μJ with 8ns pulses at 266nm, 10Hz), with high enough photon energy to excite the usual luminescent screens. First, relative sensitivity measurements were done to qualify the method with respect to a beam measurement. The results of this test are given in Table 3. The measurements give results similar to the ones obtained with proton beams, except for the Ce doped Glass which emits in a wide band around 395nm, probably too close to the laser wavelength.

To assess the screen resolution, measurements can be performed in a beam line, but they will be limited by the smallest achievable beam size. This will be easier with a laser beam. In a first test, the laser beam was focused to a small spot, and the beam sizes were measured for the various screens, a method which lacked sufficient precision. To progress further, a "pepper pot" type mask was inserted before the screen, to image onto the screen a pattern of light spots of 210μm diameter at a pitch of 380μm. The Contrast Function of this pattern was measured, and the resolution, expressed as the rms beam size broadening, was deduced from it: see Fig. 7.

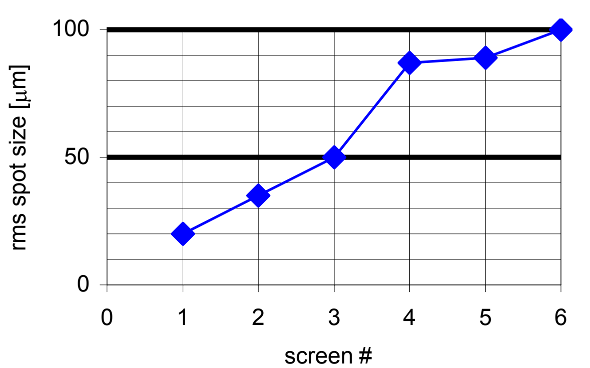

Figure 7: Resolution of different screens: given is the rms spot size for a point beam. The first screens are the P43, CsI and YAG, the others are various Al_2O_3 screens.

A clear separation is visible between the first three screens and the others. It is evident from this plot that the very thin phosphor screen and the crystalline screens will give a better resolution than any ceramic screen. These results were obtained with an IR filter, which improves significantly the resolution while decreasing the sensitivity for the Al_2O_3 screens. The test has shown that the influence on the resolution of the screen material thickness is more important than that of the material granularity.

For OTR screens, the resolution should only be affected by optical phenomena, i.e. defocusing and diffraction. At the high gamma end of the beam energy, the diffraction due to the emission pattern has been considered in the past as preventing the use of OTR. Since then, it has been shown that this doesn't apply, and an estimate for the "blurring" of the spot size of $\sigma\sim5\lambda$, i.e. 3μm at 600nm, has been published [10] and deduced from experiments [9]. On the low gamma range, cutting into the OTR distribution decreases the sensitivity and can produce diffraction, see Fig.4 for the angular extension of OTR. But as in this energy range the beams are in general big, this limitation should not be serious. What will be serious is the lack of photons at the detector level. So the optics have to be optimised for the best collection of light.

OPTICS AND DETECTORS

The next items in the chain of a monitor are the optics and the detector. It is important to have reference patterns on at least one screen for precise scaling and geometric references for the whole optical chain: see Fig. 2 and 5.

The optics are non-critical items, except with OTR screens for low gamma beams where the acceptance will have to be maximised.

For the detector [11], the first selection criterion is the local radiation level. If it is high, TV tube cameras have to be used. If the radiation level is lower, solid-state detectors can be used. For not too high levels, CID cameras can be installed. With low radiation levels, CMOS or CCD cameras can be used. The next factor to take into account is the matching of the detector sensitivity to the light emission of the luminescent screens. Given below in Fig. 8, are the emission and sensitivity spectra of various screens and detectors.

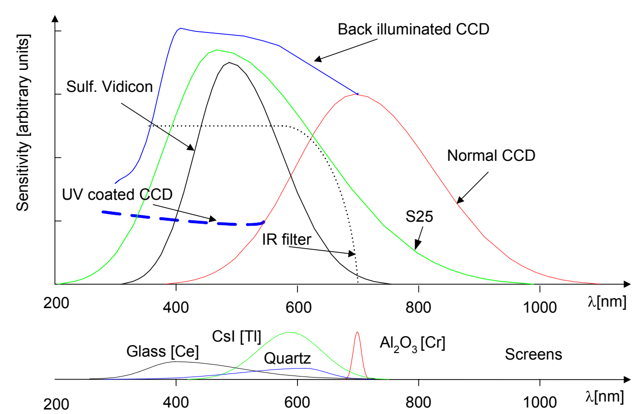

Figure 8: sensitivity and emission spectra of various detectors and screens.

It can be seen that a Glass [Ce] screen is not matched to a normal solid-state camera and that with an Al_2O_3[Cr] screen it has to be checked if the camera is fitted or not with an IR filter, as can be the case for improving camera resolution. The light level generated has to be matched to the detector sensitivity. Table 1 will be of help for this choice. Attention has to be paid to the control of the light level impinging on the detector as a test with the laser beam and an Al_2O_3[Cr] screen has shown. In this test, the beam size was measured either with only the laser beam attenuated to stay below CCD "blooming", i.e. visible over-exposure on a TV monitor, or with additionally the screen generated light attenuated to stay well below CCD saturation as measured on an oscilloscope: see Fig. 9.

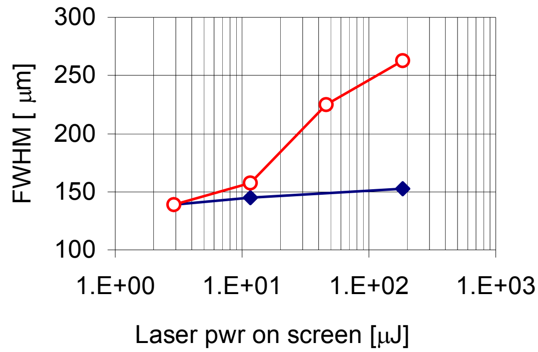

Figure 9: Beam sizes measured with attenuation of the laser beam (top curve) to prevent CCD "blooming" and with additional attenuation of the light emitted by the screen (bottom curve) to stay well below CCD saturation.

It is clear from these curves that the screen is not introducing a beam broadening through "saturation" by more than 7% over nearly two orders of magnitude of laser power, but the camera does, at a level of saturation not visible on a TV monitor. This test shows the importance of being able to control the light level on the sensor by optical attenuators, the aperture control or the integration time of the detector if slow screens are used.
If fast profiles are to be acquired, such as beam time structure in transfer lines or turn-by-turn profile information in a circular machine, either OTR screens or fast crystalline screens and specific detectors have to be used. Fast digitised cameras with or without MCP intensifier/shutter, or multi-anode photomultipliers have to be used. Given below in Fig.10 is a sequence of profiles measured at a rate of 10kHz with a MCP gated camera.

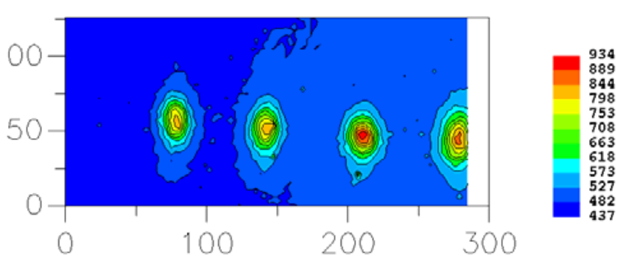

Figure 10: multiturn profile measurements with an OTR screen and a MCP Intensified camera in the SPS ring.

For very fast observations, as for measuring longitudinal profiles of bunches, a streak camera can be used [12].

While CCD detectors capture the beam image over their integration time, normally 20ms in the CCIR standard, before storing it in their memory area, CMOS cameras read their photodiodes sequentially over the 20ms frame time and TV tubes explore sequentially the odd and even lines of the picture. The automatic exposure and gain controls of CMOS cameras can give rise to problems when using fast screens. In certain cases the beam will simply be missed when using the "rolling shutter" asynchronously to the beam passage. In other cases, the integration time will be pushed to its maximum during the beam off period, which will saturate the detector at beam passage. If position measurements are also to be performed with the screen monitor, attention has to be paid to the sensor type. For a TV type detector, it has to be remembered that a complete image is built from two frames, comprised of the even and the odd lines. A TV tube explores these lines in sequence and in a CCD the two frames are generated from two full scenes shifted on the detector by half a pixel. This will result in a computed vertical centre of charge offset of half a pixel between odd and even frames. This miscalculation will not occur with a CCD working in "progressive scan" mode.

OTHER MONITORS

Other monitors can be used, depending on the beam energy and intensity. Due to lack of space, we can't develop in detail these alternatives.
For high intensity hadron beams, gas luminescence has been used successfully at Los Alamos [13]. While this was considered only useful at low energy, tests in the CERN PS and SPS with Nitrogen and 1 to 450 GeV protons have shown that such monitors can also be used up to high energies [14]. This could be interesting at energies where OTR is not producing light in a reasonably sized acceptance or where small beam sizes at high intensity are a risk for screen survival [15]. The tuning parameter here is the gas pressure, which can go up to atmospheric pressure with separation windows.
For high gamma beams, for instance leptons above a few hundred MeVs, synchrotron light monitors can be implemented using the beam line bending magnets. This will result in a non-interfering profile monitor with an excellent time response, which can be a substitute for OTR screens. Good results were obtained in the MIT Bates transfer line to the South Hall with a 315 MeV electron beam and a 90° bending magnet [16].
Diffraction Radiation may be another method worthwhile considering for a non-intercepting monitor [17].

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