DESIGN ALTERNATIVES FOR BEAM HALO MONITORS IN HIGH INTENSITY ACCELERATORS

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Abstract

In future high intensity, high energy accelerators it must be ensured that particle losses are minimized as activation of the vacuum chambers or other components makes maintenance and upgrade work time consuming and costly. It is imperative to have a clear understanding of the mechanisms that can lead to halo formation and to have the possibility to test available theoretical models with an adequate experimental setup.

Optical transition radiation (OTR) provides an interesting opportunity for linear real-time measurements of the transverse beam profile with a resolution which has been so far at best in the some μm range. However, the dynamic range of standard OTR systems is typically limited and needs to be improved for its application for halo measurements.

In this contribution, the existing OTR system as it is installed in the CLIC test facility (CTF3) is analyzed and the contribution of each component to the final image quality discussed. Finally, possible halo measurement techniques based on OTR are presented. Later beam tests are foreseen to be carried out in CTF3.

INTRODUCTION

Optical transition radiation is produced when charged particles pass through media with different dielectric constants. It took about 10 years from the first demonstration of its practical application for measuring a wide range of important beam parameters [1] until it was used in a number of accelerators as one of the main diagnostic tools [see for example 2, 3].

Since then, OTR has proven to be a flexible and effective diagnostic method for measuring a wide range of beam parameters like the beam profile, its divergence and the beam emittance. Its fast time response in combination with e.g. a streak camera makes it the ideal tool even for the analysis of the longitudinal beam shape in single shot measurements.

In order to be applicable for investigations of the beam halo, i.e. measurements with large differences in intensity between the beam core and the tail region, a highly optimized diagnostic system is needed, where the influence of all components on the final data is known in detail.

In CTF3, different constraints have to be respected, which directly influence possible measurement techniques: The high radiation level in the machine

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requires special shielding of the CCD cameras used and the power deposited in the screen limits the type of material of the screens. Either Aluminum or carbon screens are used depending on whether the focus lies on high reflectivity or good thermal resistance.

To get a better understanding of the characteristics and present limitations of the optical systems used in CTF3 at the moment and to find possible improvements systematic measurements and associated simulations were started.

ANALYSIS OF THE LENS SYSTEM

If a charge q hits a boundary surface with an oblique incidence, the emitted electric field has two components: One in the plane of observation and the other one perpendicular to it. The total emitted intensity W of a beam with a given relativistic γ therefore has to be calculated as the sum of these to components [1]

$$
\begin{aligned}
\frac{d^2W}{d\Omega d\omega} &= \frac{d^2W_{\parallel}}{d\Omega d\omega} + \frac{d^2W_{\perp}}{d\Omega d\omega} \\
&\approx \frac{q^2}{\pi^2 c} \frac{\theta^2}{\left(\gamma^{-2} + \theta^2\right)^2}
\end{aligned}
\tag{1}
$$

By direct differentiation of equation (1), the maxima of the resulting intensity distribution can be found at angles $\theta_{max}=1/\gamma$. In calculations with the ZEMAX code [4], this opening angle was used as one initial parameter to qualify the lens systems installed at CTF at different energies.

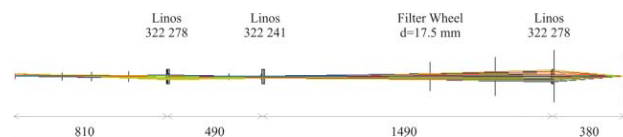A typical installation consists of a set of achromats as shown in the following Fig. 1.

Figure 1: Overview of an optical line as it is presently used in CTF3

With ZEMAX, a detailed analysis of the present installation was performed to find out the main limiting factors.

It was found that, in contrast to the existing systems, the two first lenses should be installed in a so-called confocal arrangement, i.e. where the lens spacing equals

the sum of the focal lengths, to preserve linearity for both position and angle measurements.

Furthermore, it turned out that, particularly with regard to higher energies, homogenous illumination of the detector is only reached for very small object sizes, Fig. 2 – mainly due to vignetting in the lenses.

This effect clearly limits the performance of the system and needs to be avoided in halo measurements where one is mainly interested in measuring larger distances from the beam center with high accuracy.
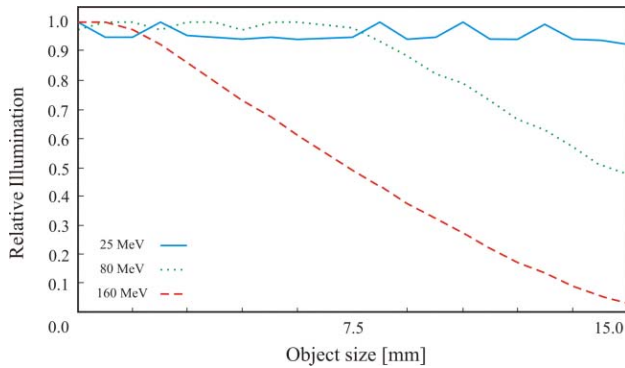

Figure 2: Calculated relative illumination of a standard optical line in CTF3 at beam energies of 25 MeV, 80 MeV and 160 MeV.

These limitations were also found in measurements done at CTF3. The following Fig. 3 shows the measured vertical profiles of a 100 MeV beam as a function of the horizontal dipole magnet current (i.e. center position). In this measurement, the entire width of the screen was scanned and a homogeneous illumination should be expected. The decreasing intensity observed towards the screen boundaries clearly indicates strong limitations of the angular acceptance of the optics.
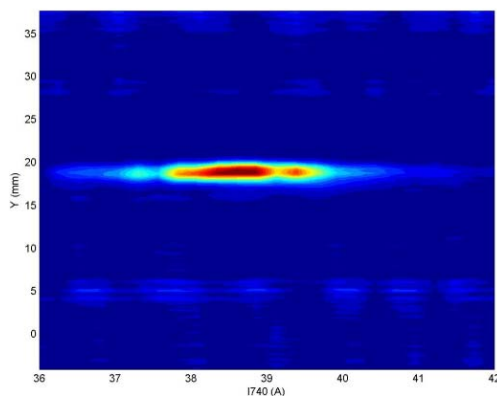

Figure 3: Measured vertical profiles of the OTR light of a 100 MeV beam at different bending fields

SCREEN SURFACE

Different ways to improve the relative illumination of the system are feasible and one way is to modify directly the light emitted from the OTR screen. Since there are strong constraints due t the high radiation level in the machine, the number of usable materials is reduced to a few. The emission distribution of the backward OTR light is proportional to the diffusive (R_D) reflection of the screen surface

$$\theta \propto R_D \qquad (2)$$

Thus one would like to increase the opening angle q while keeping the number of emitted photons as high as possible. The main goal therefore was to find out how well the diffusion of the incident light can be controlled, since this parameter helps to avoid the sharp emission profile of OTR that gives rise to the present limitations.

Table 1: Overview of applied surface treatments

Number	Description of surface treatment
1	Direct illumination of photomultiplier tube
2	Mylar foil + Aluminum
3	Reference plate, mechanically polished
4	Silver-plated
5	Sand blasting
6	Degreasing
7	Degreasing + HNO_3 + HF
8	Degreasing + HNO_3 + HF + NaOH
9	Glass bead blasting
10	oxidation
11	unpolished

In a series of measurements, Aluminum plates were first mechanically polished to mirror quality and then systematically depolished by applying different techniques summarized in Table 1.

Figure 4 shows the measured total reflection of the different screens, measured with a photomultiplier tube type XP2020 and a psec laser pulse.
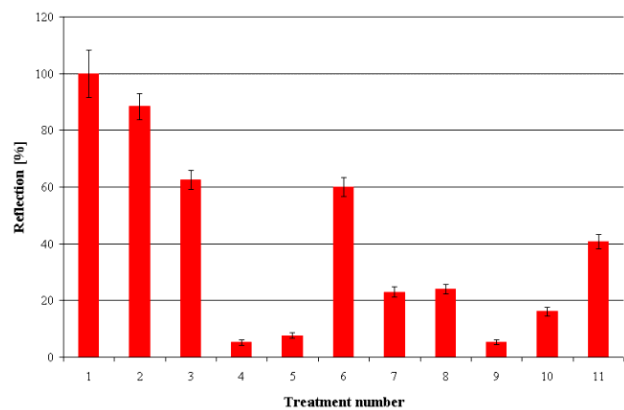

Figure 4: Measured total reflection of different surfaces within the angular acceptance of the PMT

Depending on the applied treatment the absorption of light changes over a wide range. It can be seen from the graph that in some cases not more than 5% of the light is detected, which has to be taken into account during the estimation of the sensitivity of the final detection system.

The angular divergence was measured with a CCD camera and a small cw laser. The resulting angles after reflection can be seen in the following Fig. 5.
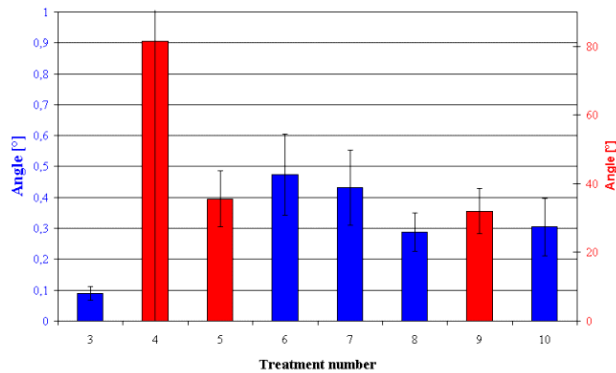

Figure 5: Measured angular divergence of the reflected beam of different surfaces. Either small angles or very large divergences were measured (the color of the bars indicates which scale to use).

The influence of the surface treatment on the diffusion can clearly be seen and these first measurements showed already that it is possible to vary this parameter over a wide range.

Next steps will focus on the properties of different metals and reaching controlled and reproducible effects with different treatments.

Another option is to influence the emitted light by the shape of the screen itself rather than modifying its surface characteristics. Due to the geometrical limitation of the present system especially in the spectrometer lines of CTF3, where the beam is ribbon-like, not all light emitted from the screen surface can be captured with the optical system.

A parabolic foil support could be a possible solution since it might allow capturing more light by the optical system due to the initial focusing of the emitted light. The surface of the screen is described by:

$$z = \frac{1}{4 \cdot f} \cdot x^2 \qquad (3)$$

where z is the vertical surface coordinate, x is the horizontal displacement from the center and f is the desired focal length.

A prototype with a focal length of $f = 500\ mm$ which can hold foils of a thickness of $d = 0.2\ mm$ has been manufactured and is presently under investigation.

MEASUREMENT TECHNIQUES

At present, standard CCD cameras are used at CTF3 for beam profile measurements. To overcome their limitations concerning at the same time spatial resolution and in particular dynamic range, alternatives are being studied.

Beam collimation technique

By putting a mask with only one or a few small holes in an image plane of the optical line and by thus collimating most of the OTR light, measurements with large dynamic ranges are feasible. In such an arrangement, small PMTs are placed right behind these apertures and allow integration of the incident light over variable time periods. By putting the complete setup on a stepping motor, the complete image can be scanned systematically.

Core masking technique

Developed originally for corona measurements in Astrophysics, a core masking technique might also be beneficial for halo studies and a first setup has already been tested at CTF3 [5]. This technique was mainly limited due to the usage of a fixed-size mask and the limited performance of the CCD camera used.

Improvement of the camera system

Since the CCD cameras used in the present installations clearly limit the dynamic range of the measurements, alternatives are being investigated. CID cameras offer the possibility to read out single pixels without deleting the image information and thus allow integration of the measurements over longer time periods and thus increase the sensitivity enormously. Without the need of a mask or collimator, direct image detection with large dynamic ranges might be possible and will be tested.

CONCLUSION

A number of different effects directly affect the results of high resolution OTR measurements: The way how the radiation is created, i.e. the quality and shape of the screen surface determines the initial light distribution. Their control might thus be a way to optimize the final image quality particularly important for halo measurements. Furthermore, the optical imaging system itself, the quality and type of lenses and mirrors influence the final image. All these components and the measurement technique determine the final layout of the halo measurement system.

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