ELECTRON BEAM PROFILE DETERMINATION: THE INFLUENCE OF CHARGE SATURATION IN PHOSPHOR SCREENS*

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Abstract

In this work we describe a model to study the effect of charge saturation in phosphor screens in the determination of electron beam profiles. It is shown that the charge saturation introduces systematic errors in the beam diameter determination, since it tends to increase the observed beam diameter. The study is made supposing a Gaussian beam profile and a saturation model to the charge response of the phosphor material. The induced errors increase for higher currents and/or narrow beams. A possible correction algorithm that can be applied to some measurements is presented, together with a brief discussion about the consequences of these systematic errors in emittance measurements.

INTRODUCTION

Beam imaging is based on some process of light production. This process can be, for example, Optical Transition Radiation (OTR). In this process, the intensity of the emitted radiation is a linear function of the incident charge, therefore the image generated by OTR emission is proportional to the beam charge distribution. This makes OTR a very good process to produce light for beam imaging [1].

However, if the process is non-linear, the beam image is a distorted representation of the beam charge distribution. This phenomenon is well illustrated in reference [2].

An example of non-linearity is observed if the light intensity becomes constant, even if the incident charge is increased (saturation). In this work, we discuss the influences of this saturation on phosphor screens, that are widely used for beam imaging in accelerators.

It will be shown that charge saturation introduces systematic errors in the beam diameter determination, since it tends to increase the observed beam diameter.

This phenomenon is relevant to higher currents and/or narrows beams in observations with phosphor screens with slow response.

We also propose an algorithm to make a correction on the observed beam diameter in order to estimate the actual beam diameter.

MODEL OF SATURATION AND ITS EFFECTS

To analyze the influences of charge saturations on phosphor screens, it is necessary to model the response of the phosphor to an incident charge. We suppose a saturation model with the form:

$$I(i) = I_{max}.\left[1 - \exp\left(-\lambda i\right)\right] \quad (1)$$

where I is the light intensity produced by the incidence of a current i, I_{max} is the intensity of the light in saturation condition, and λ is a constant related to how sensitive is the material to the incident charge. Materials with higher λ saturates with lower currents, while materials with lower λ saturates with higher currents.

We study the effects of saturation, as described by equation 1 on an "unidimensional" beam with a gaussian charge distribution, given by:

$$i(x) = \frac{i_0}{\sqrt{2\pi}\sigma}\exp\left(-\frac{x^2}{2\sigma^2}\right) \quad (2)$$

where i_0 is the total beam current, x is the position relative to the center and σ is the standard deviation of the distribution. Using equation 2 on 1, we have the expression for the observed distribution:

$$I(x) = I_{max}.\left[1 - \exp\left(-\frac{1}{\sqrt{2\pi}}\frac{\lambda i_0}{\sigma}\exp\left(-\frac{x^2}{2\sigma^2}\right)\right)\right] \quad (3)$$

Since the term $\exp(-x^2/(2.\sigma^2))$ is limited to the interval]0;1], the influence of charge saturation is strongly dependent of the parameter $i_0.\lambda/\sigma$. This term, that we call saturation factor, is higher for high currents and narrow beams incident on sensitive phosphor screens.

Figure 1 shows the ratio between the actual standard deviation of the beam ($\sigma = \sigma_{actual}$) and the one based on the observed light distribution ($\sigma_{observed}$) as a function of the parameter $i_0\lambda/\sigma$.

With the previous knowledge of the saturation factor, one would be able to determine the correcting factor k. Figure 2 shows the influence of the constant λ in the beam charge distribution (for λ = 1, 10 and 100). The full line represents the observed distribution, while the dashed line represents the actual charge distribution.

It is possible to observe that the standard deviation of the observed distribution increases with λ, consequently inducing a systematic error in the beam diameter determination.

The problem with the results shown in Fig. 1 is that, in general, the constant λ is unknown. For this reason, it was elaborated the graph presented in Fig. 3 that express a relation between the correcting factor k as a function of the fraction of the half width on half maximum (HWHM) and

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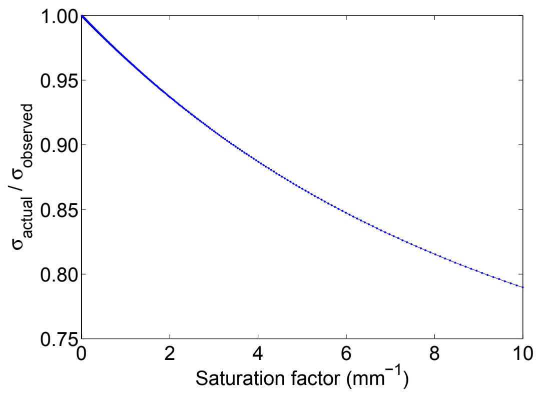

Figure 1: Ratio $k = \sigma_{actual}/\sigma_{observed}$ as function of saturation factor.

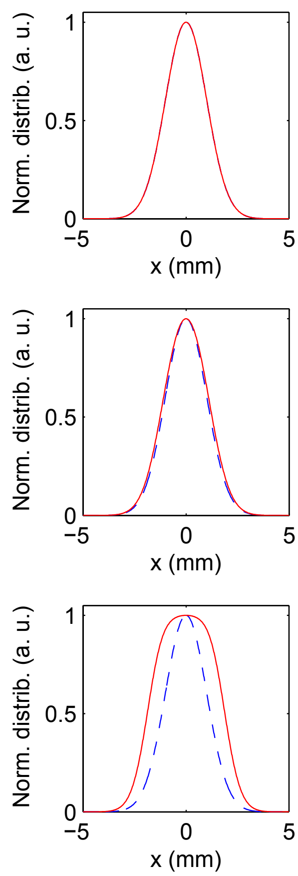

Figure 2: Comparison between the observed beam distribution (continuous line) and the actual beam charge distribution (dashed line) for saturation factor of 1, 10 and 100, respectively.

the standard deviation, both measured in the observed distribution.

The proposed algorithm to make a correction of the standard deviation measured from the phosphor screen image consists of determining the ratio $x_{HWHM}/\sigma_{observed}$ in the observed image and to find in the graph of Fig. 3 the corresponding correcting factor. Note that Fig. 3 is independent

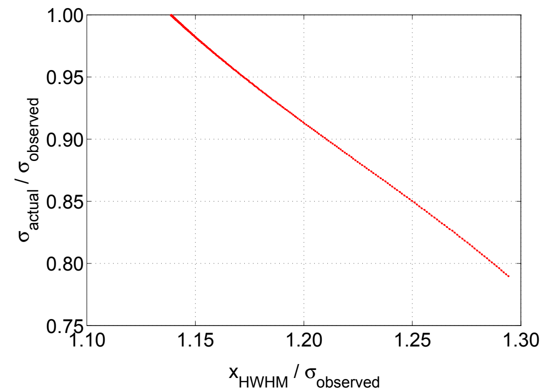

Figure 3: Ratio $\sigma_{actual}/\sigma_{observed}$ as function of $x_{HWHM}/\sigma_{observed}$.

of a previous knowledge of the constant λ or the saturation factor.

In a regular gaussian, the ratio $x_{HWHM}/\sigma = \sqrt{2.\ln 2} \approx 1.18$, therefore this is the minimum value of $x_{HWHM}/\sigma_{observed}$ to be observed in gaussian beams. For this value we find, in Fig. 3, the correcting factor $\sigma_{actual}/\sigma_{observed} = 1$.

CONSEQUENCES ON BEAM EMITTANCE MEASUREMENTS

Beam emittance can be measured by many methods, but, in order to analyze the influence of the charge saturation in phosphor screens, we will take the method described in reference [3]. This method consists of measuring the beam diameter using two different phosphor screens separated by a distance L, free of fields, where the second observation point is a beam waist.

The emittance can be calculated using the formula:

$$\epsilon^2 = \frac{R_1^2.R_2^2 - R_2^4}{L^2} \quad (4)$$

where R_1 (R_2) is the beam diameter in the first (second) phosphor screen.

As the second observation point is a beam waist, we have $R_1 > R_2$. Both of them are measured with phosphor screens and in saturation condition, so they must to be corrected. This implies that:

$$\frac{\epsilon^2_{actual}}{\epsilon^2_{observed}} = \frac{R^2_{1actual}.R^2_{2actual} - R^4_{2actual}}{R^2_{1observed}.R^2_{2observed} - R^4_{2observed}} \quad (5)$$

Supposing that $R_{1observed}$ and $R_{2observed}$ must be corrected by approximately the same factor k (obtained in Fig. 3), the beam emittance must be corrected by a factor k^2.

$$\frac{\epsilon_{actual}}{\epsilon_{observed}} = k^2 \quad (6)$$

As the factor k is always less than unity, then the observed emittance is bigger than the actual emittance.

As an example, let us suppose the beam profiles illustrated in Fig. 2. The first profile does not need corrections, since the saturation factor is equal to zero ($\lambda \to 0$). The other two profiles, for which we can obtain a factor $x_{HWHM}/\sigma_{observed}$ = 1.22 and 1.48, respectively, need correction (obtained on the Fig. 3) of 0.97, and 0.80, respectively. The corresponding emittances must be correted by factors 0.94 and 0.64, respectively. This implies that, in these conditions, the measured emittances are approximately 6% and 36% higher than the actual beam emittances.

CONCLUSIONS

In this work we studied the influence of charge saturations in phosphor screens on beam profile determination. The analysis supposed a gaussian beam profile, and assumed a model for the charge saturation process.

It was shown that saturation introduces a systematic error in the diameter measurements, and an algorithm to correct this effect was proposed.

We also discussed the influence of these systematic errors in beam emittance measurements, where they are particularly critical.

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