STUDIES OF OTR ANGULAR DISTRIBUTION ON CTF2

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Abstract

Optical Transition Radiation (OTR) is widely used in beam diagnostics. The most common application is the acquisition of the transverse and longitudinal beam profiles. Other beam parameters, like divergence and energy, can also be deduced from the angular distribution of the OTR emission ("Doughnut"). In order to investigate the possibilities and the limits offered by this technique we have performed a test on the 48MeV, 1nC electron beam of the CLIC Test Facility 2 (CTF2.). Beam divergences between 2 and 6mrad were measured with an accuracy of a few percent. A good agreement was also found between the energy measurements obtained with a classical spectrometer and the OTR based technique. We conclude by describing some possible applications of OTR based diagnostics for CLIC.

1 INTRODUCTION

Optical Transition Radiation [1] has become a familiar tool in accelerator diagnostics for beam imaging [2]. Its success resides in its simplicity, only requiring a conducting foil and an adequate optical system, providing thus a robust and cheap instrument. The perfect linearity of the light intensity versus the number of particles is a significant advantage compared to scintillating screens, which are subjected to saturation. Its femtosecond time resolution [3] allows accurate bunch length measurement, limited in most cases by the performance of the camera. Using the so-called 'quadrupole scan method', beam emittances are routinely extrapolated from OTR beam profile measurements. As already pointed out in the '70s, much more information than the beam profiles can be extracted from the OTR emission [4]. The beam energy and divergence are accessible in the angular distribution of the OTR. In this case, the camera must be located in the focal plane of the optical system, which is focused at infinity. A lot of experiments have been done in this direction during the past years, demonstrating the strong potential of transition radiation for single shot emittance measurement [5] or beam energy and energy-spread determination [6]. OTR interferometry using a two-foil assembly has been also developed [7] and has shown its capability to enhance the performance of the OTR angular techniques.

In this paper, we report on the OTR study performed at the CLIC Test Facility 2 (CTF2) [8] using a 48MeV, 1nC electron bunch. Our effort has been concentrated on the angular distribution observation. Beam divergences were measured with a good accuracy and OTR based energy measurements have been compared with success to the classical energy measurements performed with a spectrometer line. We finally give some perspectives for its utilization in the CLIC context [9].

2 OTR FOR RELATIVISTIC PARTICLES

Let us consider the interface between vacuum and a material with a relative permittivity ε. Let us also assume that this interface is tilted with respect to the beam trajectory by an angle ψ, as shown in figure 1. Using the formalism developed in [4], the backward OTR spectral and angular distribution emitted with polarizations parallel and perpendicular to the observation plane can be expressed by:

$$\frac{\partial^2 I_{//}}{\partial\omega\,\partial\Omega} = \frac{\alpha\cdot\hbar}{4\pi^2}\,\frac{\beta_z^2\cos^2(\theta)}{\sin^2(\theta)}\left|\frac{(1-\varepsilon)\left(A\cdot\sin^2(\theta)-B\right)}{C\cdot D\cdot E}\right|^2$$

$$\frac{\partial^2 I_{\perp}}{\partial\omega\,\partial\Omega} = \frac{\alpha\cdot\hbar}{4\pi^2}\left(\beta_x^2\beta_z^4\sin^2(\phi)\cos^2(\theta)\right)\left|\frac{(1-\varepsilon)}{C\cdot D\cdot F}\right|^2$$

with $\beta_z = \beta\cos(\psi)$, $\beta_x = \beta\sin(\psi)$, α the fine structure constant, $\hbar$ the reduced Planck constant and the following functions defined by:

$$A = 1+\beta_z\sigma-\beta_z^2-\beta_x\sin(\theta)\cos(\phi)\ ,\ \mathrm{B} = \beta_x\beta_z\sigma\sin(\theta)\cos(\phi)$$

$$C = \left(1-\beta_x\sin(\theta)\cos(\phi)\right)^2-\beta_z^2\cos^2(\theta),\ \mathrm{D} = 1-\beta_x\sin(\theta)\cos(\phi)+\beta_z\sigma$$

$$E = \sigma+\varepsilon\cos(\theta)\ ,\ \mathrm{F} = \sigma+\cos(\theta),\ \sigma = \sqrt{\varepsilon-\sin^2(\theta)}$$

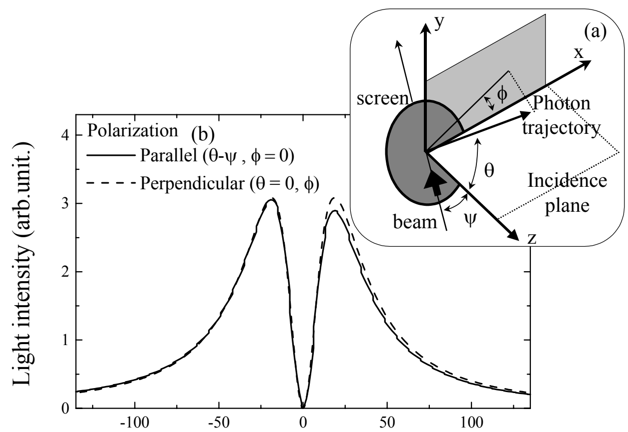

Figure 1: (a) Geometrical configuration: The incident plane contains both the normal to the screen and the beam velocity (b) OTR angular distribution, $I_{//}$ and $I_\perp$ for a 50MeV electron. The tilt of the screen introduced an asymmetry of the lobes pattern, only visible in the $I_{//}$ signal. The relative position of the maximums with respect to the centre of the distribution gives a measurement of the beam energy ($=1/\gamma$).

Assuming that the electron beam has a Gaussian angular distribution defined as follow:

$$D_{//,\perp}(s) = \frac{e^{-\frac{s^2}{2\sigma'^2_{//,\perp}}}}{\sqrt{2\pi}\cdot\sigma'_{//,\perp}}$$

The angular distribution of the OTR light is obtained by the convolution of $I_{//,\perp}$ and $D_{//,\perp}$. Some examples are given in figure 2 assuming different beam divergences. In this calculation $\theta = \psi$, so that $I_{//}$ vanishes. Two important considerations result from this analysis: first there is a limitation in the minimum beam divergence measurable. For divergence lower than 1/10γ, the divergence of the beam cannot be extracted from the OTR angular distribution. Secondly the angular distribution is diluted by the beam divergence so that for divergences above $1/\gamma$, the lobes pattern disappears making the beam energy measurement impossible.

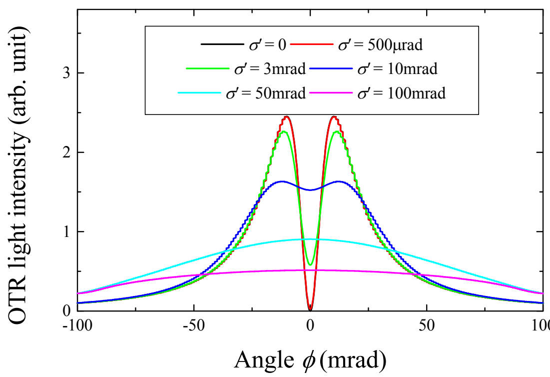

Figure 2: OTR angular pattern for different values of beam divergence

3 EXPERIMENTAL SET-UP

The layout of the CTF2 probe beam line is shown in figure 3.

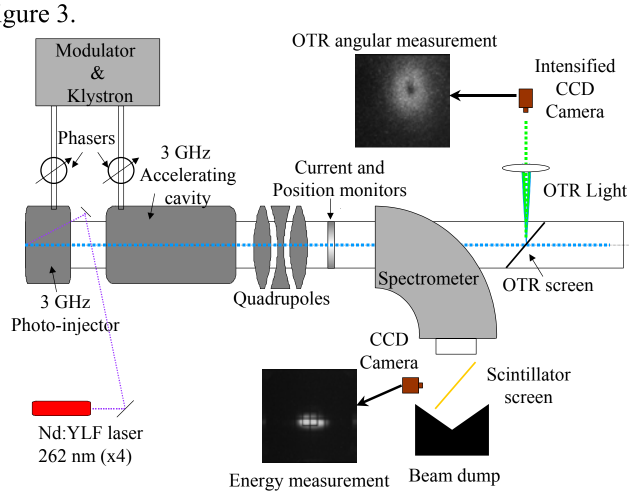

Figure 3: OTR test on the CTF2 probe beam line

A Nd:YLF laser 256nm (frequency quadrupled) is used to run a 3GHz radiofrequency photo-injector. Typically one 1nC electron bunch of 4ps FWHM length is produced and accelerated to a nominal energy of 48MeV in a normal conducting 3GHz accelerating structure. A spectrometer line, consisting of a bending magnet and a scintillating screen placed outside of the vacuum chamber, is used for the characterization of the beam energy and the tuning of the RF accelerating phase. An OTR screen has been inserted just downstream of this bending magnet. The target consists of a 100µm thick aluminized Mylar foil, tilted by 45° with respect to the electrons trajectory. The optical system is composed of an achromat lens with a 80mm focal length and an intensified CCD camera located at the focal plane. The distance between the centre of the OTR screen and the lens is set to 75mm allowing an angular aperture of 130mrad (around 10/γ).

4 OTR MEASUREMENTS

The image analysis is performed as follow; we first determine the centre of the OTR 'doughnut', around this position thin slices along the vertical and horizontal direction are selected and compared to our calculations. A minimization fit gives then the energy and the divergence of the beam.

2.1 Divergence measurements

The divergence of the beam on the OTR screen is adjusted by varying the current in the upstream quadrupoles. A set of 8 images is acquired for each current value in order to have sufficient statistics. The results are summarized in figure 4 with the OTR 'Doughnut' images and the corresponding projections ($I_{//}$) superimposed with the theoretical fit calculations. The OTR 'Doughnut' is getting blurred when the divergence increases. Divergences from 2 to 6mrad were measured with an accuracy of a few percent, limited by the performance of the CCD (8bits coding) and the noise level (ambient light background and noise from the image intensifier).

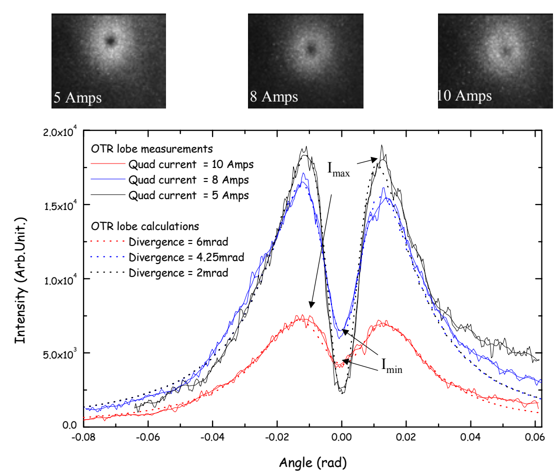

Figure 4: OTR angular distribution for three different beam divergences

2.2 Energy measurements

By changing the modulator voltage it is possible to control the beam energy. In figure 5 are shown the OTR angular distribution obtained for 4 different voltages. The RF phases of the gun and of the accelerating cavity are adjusted to obtain minimum energy dispersion. This was checked using the spectrometer line before each OTR measurement. Images, slices and fitted curves are displayed for each case. The performance of the energy measurement depends mainly on the optical system. The distance between the screen and the lens fixed the range of measurable energy, and together with the size of our CCD pixels give the precision of the measurements. In our set-up this leads to an direct accuracy of 1MeV.

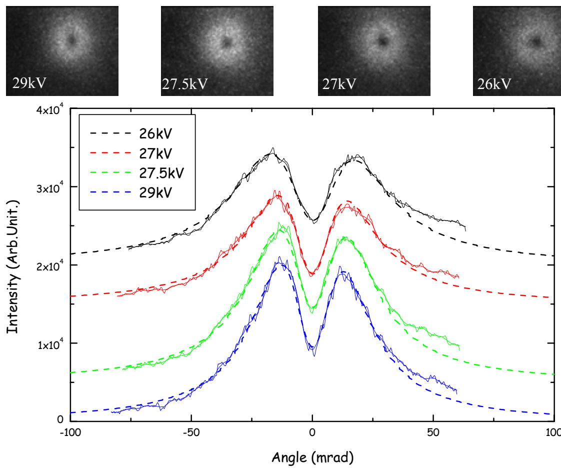

Figure 5: OTR angular distribution for different beam energy

The results, summarized in table 1, show that the agreement between spectrometer and OTR measurements is very good for the two first voltage values. A discrepancy of 10% is then observed, possibly due to aberrations in the optical system or a misalignment of the electron beam entering the spectrometer line, which is very sensitive for energy measurements.

Table 1: Energy variation measurements

Modulator voltage (kV)	29	27.5	27	26
Spectrometer line (MeV)	48	45	*43.2*	*39.6*
OTR images (MeV)	47.2	44.6	*40.5*	*36.3*

A second set of data has been acquired to try to measure the electron energy dispersion. Results for different tunes of the RF accelerating phase are given in figure 6.

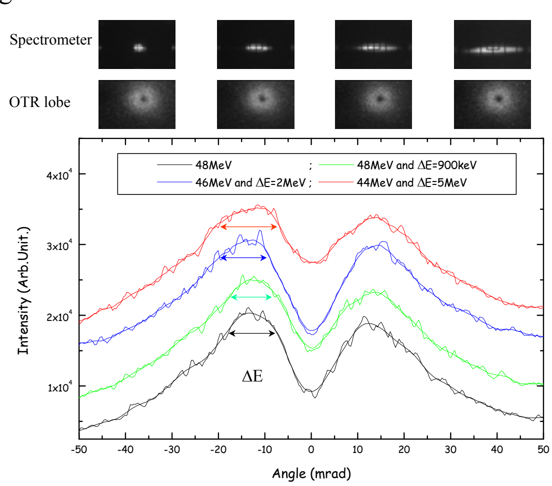

Figure 6: OTR angular distribution for different energy dispersion

To extract the energy dispersion from the OTR image, a more complex analysis is necessary. We measure the width (ΔE) of the OTR lobes at 90% intensity. The centre of this ΔE gives the average energy. The beam divergence is calculated for this central energy by fitting the I_{max} and I_{min} values. The energy spread is then obtained by subtracting the calculated monochromatic width (ΔE_{mono}) from the measured ΔE. The results are reported in Table 2 and indicate that the energy spread is slightly overestimated compared to the spectrometer.

Table 2: Energy dispersion measurements in MeV

Spectrometer	48±0	48±0.9	46±2	44 ±5
OTR images	48.1±0	48.2±1.5	45.2±2.8	43.5±6.2

5 CONCLUSIONS

The observation of the OTR angular pattern can lead to the measurement of the beam energy and divergence. On the CTF2 machine, we have been measuring divergences of a few mrad with a good precision. Beam energy and energy dispersion measurements are compatible with the values obtained with the spectrometer line.

Using an appropriate optical set-up, single shot emittance measurement can be obtained. By using a pepperpot-like method on the OTR photon beam, the whole transverse phase space can be reconstructed [10].

For the CLIC beam, a rapid calculation indicates that in the main linac the beam emittance is 10^4 too small to allow an OTR-based divergence measurement. However energy or energy dispersion could be monitored along the linac where no spectrometer line could be envisaged.

Some investigations are specially needed to check what is the impact of the screen surface quality on this angular distribution. For a thermally resistant material like carbon, one could envisage a significant perturbation of the lobes.

6 ACKNOWLEDGMENT

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7 REFERENCES

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