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OTR FROM NON-RELATIVISTIC ELECTRONS

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Abstract

The CLIC Test Facility 3 (CTF3) injector will provide pulsed beams of high average current; 5A over 1.56 microseconds at 140keV. For transverse beam sizes of the order of 1mm, as foreseen, this implies serious damage to the commonly used scintillating screens. Optical Transition Radiation from thermally resistant radiators represents a possible alternative. In this context, the backward OTR radiation emitted from an aluminium screen by a 80keV, 60nC, 4ns electron pulse has been investigated. The experimental results are in good agreement with the theoretical expectations, indicating a feeble light intensity distributed over a large solid angle. Our conclusions for the design of the CTF3 injector profile monitor are also given.

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The CLIC Test Facility 3 (CTF3) injector will provide pulsed beams of high average current; 5A over 1.56µs at 140keV. For transverse beam sizes of the order of 1mm, as foreseen, this implies serious damage to the commonly used scintillating screens. Optical Transition Radiation from thermally resistant radiators represents a possible alternative. In this context, the backward OTR radiation emitted from an aluminium screen by a 80keV, 60nC, 4ns electron pulse has been investigated. The experimental results are in good agreement with the theoretical expectations, indicating a feeble light intensity distributed over a large solid angle. Our conclusions for the design of the CTF3 injector profile monitor are also given.

1 INTRODUCTION

The injector of the CTF3 facility in the nominal phase will produce intense beams [1]. The pulse will be 1.56µs long at a repetition rate of 50Hz, the nominal average current will be 5.4A, the electron energy 140keV and the beam size of the order of 1mm ($\sigma_{x,y}$). These values render the use of standard scintillating screens impossible since they will not stand the corresponding thermal load [2]. Reducing the beam current or the pulse length during the measurement can circumvent this problem. But for the optimum machine operation the observation of the beam profile in the transverse plane up to full intensity is required. For this reason alternative techniques must be developed. One solution consists of using Optical Transition Radiation (OTR) [3] with a graphite or carbide-based radiator. At the beginning of the ‘60s a lot of work was done on the OTR theory [4], together with experiments with electrons of energies between 1-100keV[5]. With the development of accelerators, OTR from relativistic particles [6] was studied and its application as a beam diagnostic tool has been widely developed. In the case of non-relativistic particles, OTR radiation, which is less efficient than scintillation in terms of light intensity, was never used, to our knowledge, for beam profile monitoring.

In order to investigate the feasibility of using an OTR screen for the CTF3 injector, we have been carried out some measurements on the 80keV electron beam available in the photocathode test stand at CERN [7]. Our paper is organised as follows. First, the OTR light characteristics are calculated for low energy electrons, in particular the angular distribution of the radiation. The beam line arrangement of the photocathode laboratory is described including the detection system added for this test. Experimental results are compared to our theoretical expectations and some perspectives for the CTF3 injector profile monitor are finally expressed.

2 OTR EMISSION FROM NON RELATIVISTIC ELECTRONS

We consider the transition between the vacuum and a material with a relative permittivity ε. The screen is tilted with respect to the beam trajectory ($\vec{z}$) by an angle ψ, as shown in figure 1. The OTR emission results from the contribution of the direct ($\vec{n}$), the reflected ($\vec{n}'$) and the refracted ($\vec{n}''$) radiations emitted by the particle. Using the formalism developed by Wartski in [6], the backward OTR spectral and angular distribution emitted with polarizations parallel and perpendicular to the observation plane[†] can be expressed by:

$$\frac{\partial^2 I_{//}}{\partial\omega\,\partial\Omega} = \frac{\alpha\cdot\hbar}{4\pi^2}\left|\frac{\vec{\beta}_{//}\wedge\vec{n}}{1+\vec{\beta}\cdot\vec{n}} + r_{//}\frac{\vec{\beta}_{//}\wedge\vec{n}'}{1+\vec{\beta}\cdot\vec{n}'} - \frac{f_{//}}{\varepsilon}\frac{\vec{\beta}_{//}\wedge\vec{n}''}{1+\sqrt{\varepsilon}\vec{\beta}\cdot\vec{n}''}\right|^2$$

$$\frac{\partial^2 I_{\perp}}{\partial\omega\,\partial\Omega} = \frac{\alpha\cdot\hbar}{4\pi^2}\left\|\vec{\beta}_{\perp}\right\|^2\left|\frac{1}{1+\vec{\beta}.\vec{n}} + r_{\perp}\frac{1}{1+\vec{\beta}.\vec{n}'} - \left(\frac{f_{\perp}}{\sqrt{\varepsilon}}\right)\frac{1}{1+\sqrt{\varepsilon}\vec{\beta}.\vec{n}''}\right|^2$$

with $\hbar$ the reduced Planck constant, α the finite-structure constant (=1/137), $\vec{\beta}_{//}$ and $\vec{\beta}_{\perp}$ the projection of electron velocity in the planes parallel and perpendicular to the observation plane and the corresponding Fresnel coefficients defined by:

$$f_{//} = \frac{2\sqrt{\varepsilon}\cos\theta}{\sqrt{\varepsilon}\cos\theta + \sqrt{\frac{1}{\varepsilon}}\sqrt{\varepsilon-\sin^2\theta}} \qquad f_{\perp} = \frac{2\sqrt{\varepsilon}\cos\theta}{\cos\theta + \sqrt{\varepsilon-\sin^2\theta}}$$

$$r_{//} = f_{//} - 1 \qquad r_{\perp} = \sqrt{\frac{1}{\varepsilon}}f_{\perp} - 1$$

and θ the angle between the normal of the screen and the direction of the OTR photons. The characteristic of the forward OTR emission can be obtained from the previous formula replacing β_z by $-\beta_z$ ($\beta_z = \beta\cos(\psi)$).

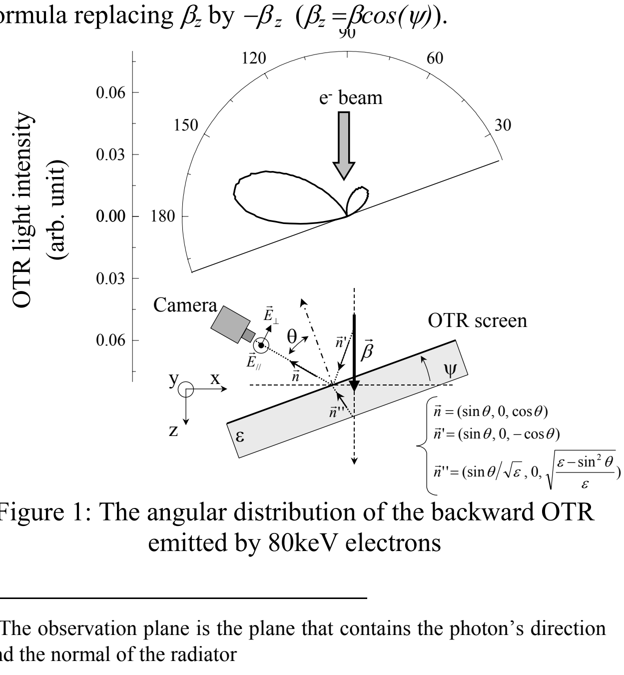


Figure 1: The angular distribution of the backward OTR emitted by 80keV electrons

[†] The observation plane is the plane that contains the photon’s direction and the normal of the radiator

The normal of the screen is tilted with respect to the beam trajectory by 20º leading to a strong asymmetry of the OTR lobes. For the forward emission, the dominant term in the OTR formula is the first term, symbolizing the direct radiation of the particle. For the backward radiation, the second term, corresponding to the reflected radiation, is preponderant and the intensity of emission will depend on the material surface state. Thus using carbon-based radiators, which have low reflectivity coefficients, will reduce the intensity of OTR light emitted by the beam.

3 PHOTO-CATHODE LAB SET-UP

The photo-cathode laboratory, as depicted in figure 2, is equipped with a photo-injector capable of producing 4ns electron pulses with an energy of 80keV and a beam charge up to 60nC. This test stand is routinely used for the development and the fabrication of the CTF2 (CLIC) photo-cathodes [8].

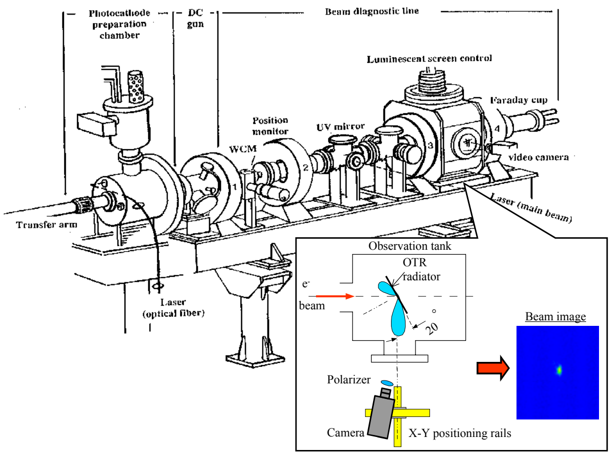


Figure 2: Layout of the electron beam line

UV pulses produced by a Q-switched Nd:YAG laser hit a Cs_2Te photo-cathode and liberate the electrons that are extracted by a DC potential of 80kV nominal. Four solenoids provide the required focusing down to the diagnostic tank installed at the end of the beam line, a couple of meters downstream.

For our test, the CsI(Tl) scintillating screen and the CCD camera normally used to observe the beam are replaced by a 1mm thick aluminium radiator and an intensified camera which can be gated to a few nanoseconds time interval. For the nominal set-up the camera is located at 50cm from the screen, providing a 20mrad detection angle. At low energies the OTR emission is getting very broad as you can see in figure 1. The screen is tilted by an angle of 20° with respect to the electron trajectory in order to send the OTR lobe in the direction of the camera.

By integrating the OTR formula over the visible range [400-700nm] and over our detection angle, the estimated number of photons per electron is $2\ 10^{-6}$, giving a signal of $7.2\ 10^{5}$ photons for the 60nC electron bunch. With this light intensity a normal CCD camera cannot be used, requiring at least 10 times more photons.

4 RESULTS

4.1 OTR identification

As the number of OTR photons is expected to be low, other sources of light in the machine can perturb our measurement. In our case, scintillation in the last laser mirror, the one used to deflect the laser beam onto the photo-cathode, was found to be the main source of background. This mirror, located close to the electron beam, can intercept the beam halo producing scintillation light. In order to identify the OTR emission we made two independent crosschecks, first looking at the polarisation of the light and secondly checking the emission duration. OTR can be considered as instantaneous compared to scintillation, which is governed by exponential decays ranging from tens of ns to ms. To disentangle the two light signals, our camera was gated down to 50ns, where the scintillation light intensity becomes very feeble. The gate duration cannot be shorter than that to take into account the intrinsic jitter of few tens of ns (typical for Q-switched laser). The transition radiation is measured and the beam profile can be obtained as shown in the picture in figure 2. One can also mention that the OTR light intensity varies from shot to shot, mainly due to fluctuations in the laser intensity (5%).

4.2 OTR emission versus beam charge

The OTR light is expected to be linear with the bunch intensity. By varying the laser pulse energy, the bunch charge can be adjusted from 20nC to 60nC. The corresponding results are given in Figure 3 by computing the total emission from the recorded images.

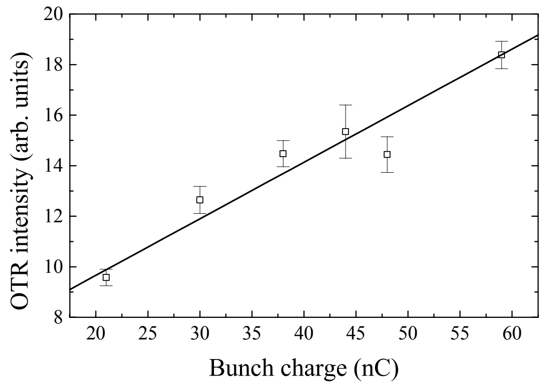


Figure 3: OTR light intensity versus the bunch charge.

The bunch charge dependence of the OTR light intensity is found to be linear with a relatively good precision. The offset due to the background is clearly seen on the fit curve. In addition to the other source of light present in the machine, noise due to the image intensifier contributes to the background level too. Error bars plotted in figure 3 are only calculated from a few shots.

4.3 OTR emission versus observation angle and distance

The camera, usually installed at 90º with respect to the beam trajectory, can be placed between 84º and 105º. Images are acquired for different observation angles and the results are displayed in figure 4 with the expected theoretical curve. A relatively good agreement is obtained, even if our experimental set-up does not permit to describe the whole OTR lobe. However it clearly indicates that 20º is not the best angle in terms of maximizing the light intensity sent to the camera (supposed to be at 90º to the beam trajectory).

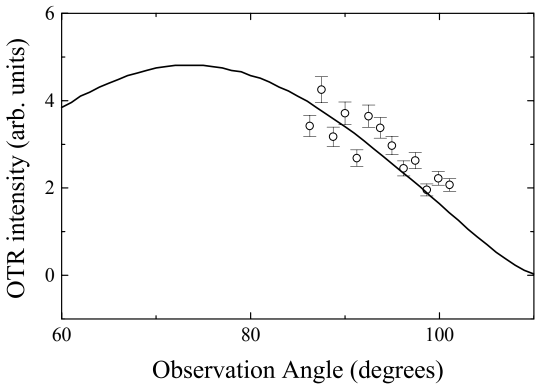


Figure 4: OTR intensity versus the observation angle.

The variation of the OTR light intensity with the observation distance has been also measured by displacing the camera over 20cm. Experimental data are shown in figure 5. The $1/d^2$ dependency is shown to illustrate the fact that the OTR emission cone for this electron energy is very large and behaves almost like an isotropic source.

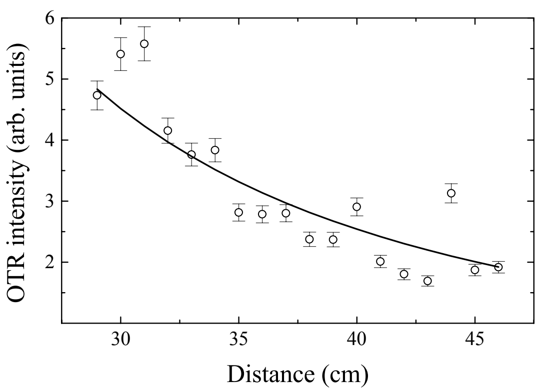
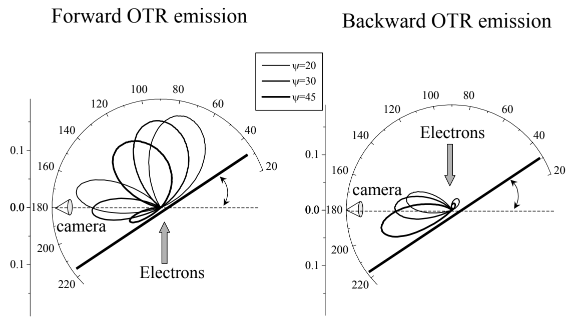


Figure 5: OTR intensity versus distance from the screen.

5 CONCLUSIONS AND PERSPECTIVES

Using the 80keV electron bunch available in the photocathode laboratory, backward OTR emission from an aluminium screen has been observed. Its characteristics, especially its angular pattern, are found to be compatible with the theoretical expectations. The light intensity is feeble and the light is emitted over a broad angular distribution, 40º FWHM.

In the case of the CTF3 injector, a carbon screen must be envisaged to stand the thermal load induced by the beam. The total reflectivity (diffuse and specular) of our carbon sample has been measured using an integrating sphere reflectometer available at the EPFL in Lausanne. The carbon reflectivity in the visible region is 26% of the aluminium reflectivity, adding thus a limitation to the use of backward OTR. From this point of view, the forward OTR emission, which is not affected by the material reflectivity, could be an interesting option. In this case very thin foils must be used to make sure that multiple scatterings occurring in the screen are not affecting the beam size at the exit interface. Moreover, it is better not to degrade the beam energy since the OTR light yield behaves like β^2 [6] at low energy. The forward and backward OTR lobes are plotted in figure 7 for different tilt angles of the screen.



Tilt of the screen (º)	20	30	45
Backward OTR (10^8 photons)	1.0	2.3	1.7
Forward OTR (10^8 photons)	7.8	7.7	0.1

Figure 6: Forward and Backward OTR emission

The total number of photons available ([300-900nm]) for detection is also calculated assuming a detection angle of 20mrad. From the lobe configuration a compromise between the light intensity and the beam aspect ratio to the screen tilt can be found using forward OTR and a 30º angle. Backward OTR, less intense, would allow a better flexibility for the choice of the tilt angle.

6 REFERENCES

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