OTR MEASUREMENTS WITH SUB-MeV ELECTRONS*

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Abstract

It is a quite common belief that beam imaging using Optical Transition Radiation (OTR), produced by sub-MeV electron beams, is impossible or at least requires special highly sensitive instrumentations. The TRIUMF electron linac, presently undergoing a commissioning stage, is capable of delivering up to 10 mA of CW electron beams. Simulations showed that such a powerful beam generates substantial amount of OTR light even at electron energies available at the output of the thermionic electron source. The experiment was then setup to test the prediction. This paper reports OTR measurements for the range of electron energies 100 - 300 keV performed with an ordinary CCD camera.

INTRODUCTION

In spite of the fact that Optical Transition Radiation has become a standard diagnostics tool in beam imaging techniques, grey areas still exist where its application requires additional studies. In particular, OTR imaging of sub-MeV electron beams is often considered impossible or at least unpractical due to low light intensity that quickly goes down with the beam energy. However, OTR techniques still remain attractive even at low energies; since they do not suffer from saturation effects inherent to scintillating materials, OTR targets do not charge up and can typically sustain much higher beam powers. Several studies were dedicated to the subject over the last few decades. Successful observation of beam images from 1 MeV electron beam with a CCD camera was reported in Ref. [1]. A decade later OTR imaging was applied to an 80keV electron beam [2]. This time a weak light dictated the use of an intensified camera. With the help of an intensifier, OTR images were obtained even for 10 keV electrons [3].

Higher beam intensities available with long pulse or CW superconducting accelerators make low energy OTR imaging nearly as routine as at multi-MeV beam energies. At the TRIUMF electron accelerator, an ordinary CCD camera was adequate to observe beams with the energy of 100 - 300 keV (β in the range of 0.2 - 0.6).

GEOMETRY OPTIMIZATION

Planning of low energy OTR measurements requires careful optimization of the experimental geometry in order to maximize the light intensity. It is very well known that for highly relativistic ($\gamma \gg 1$) particles, OTR light from a metallic mirror is highly collimated around a direction which makes an angle with the normal to the mirror surface that is equal and opposite to an angle of the particle incidence, measured with respect to the same normal. When $\gamma \sim 1$ the properties are quite different: the radiation is emitted in a broad range of angles. For the case of an ideally conducting perfect mirror, the OTR energy emitted in the backward direction per unit solid angle and unit frequency interval in the plane formed by the particle momentum and normal to the surface can be found to have a simple form (see Ref. [4] and references therein):

$$W_\omega = \frac{e^2}{\pi^2 c}\beta^2\cos^2\psi\left(\frac{\sin\theta-\beta\,\sin\psi}{(1-\beta\cos(\theta+\psi))(1+\beta\cos(\theta-\psi))}\right)^2 \quad (1)$$

In this equation ψ is the angle between the beam and the surface normal and θ is angle between the normal and radiation direction. If, as it is typically the case, radiation is observed at right angle to the beam, then $\theta = \pi/2 - \psi$ and Eq. (1) is reduced to

$$W_\omega{}^{90^\circ}(\psi) = \frac{e^2}{4\pi^2 c}\beta^2\left(1+\frac{\cos 2\psi}{1-\beta\sin 2\psi}\right)^2 \quad (2)$$

In Figure 1 the quantity $W_\omega{}^{90}$ is plotted as function of the angle ψ for two beam energies of 100 keV and 300 keV.

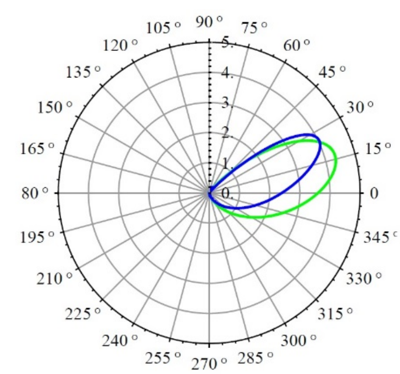

Figure 1: OTR intensity emitted at 90° to the beam direction as function of the angle $\boldsymbol{\psi}$ for beam energies 100 keV (green) and 300 keV (blue). Data plotted by the green line were multiplied by a factor of 3.

From Eq. (2) one can find that the radiation intensity reaches its maximum value

$$W_\omega{}^{90^\circ}(\psi_{max}) = \frac{e^2}{4\pi^2 c}\beta^2(1+\gamma)^2 \quad (3)$$

for an angle ψ_{max} entirely determined by the velocity of beam particles:

$$\psi_{max} = \frac{1}{2}\arcsin\beta \quad (4)$$

From Eq. (4) it follows that $\psi_{max} \to \pi/4$ when $\beta \to 1$ as one would naturally expect for a highly relativistic beam. However, for the energies of interest the intensity is rather low for $\psi = \pi/4$. Instead, Eq. (4) tells us that, optimally,

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the OTR target normal should make the following angles to the beam direction: 25.5° and 16.6° for 300 keV and 100 keV, respectively.

In our experimental setup the angle ψ was fixed to 25° and, therefore, the target tilt was optimized for measurements at 300 keV. The OTR intensity as function of the angle θ expected for such a geometry from Eq. (1) is plotted for both energies of interest in Fig. 2. The plot suggests that the 90° angle between the camera and the beam is still not optimal. Lower beam energies favour larger observation angles. However, small loss in the intensity is well compensated by practical benefits and lower beam image distortion.

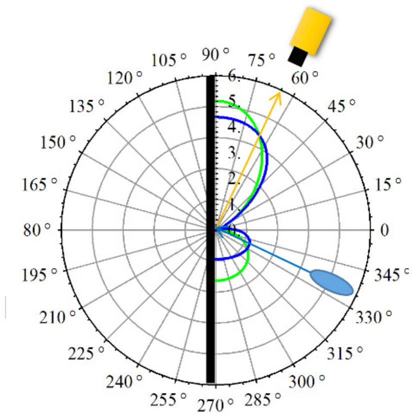

Figure 2: OTR intensity from a target tilted by an angle $\boldsymbol{\psi = 25°}$ as function of the observation angle $\boldsymbol{\theta}$ for beam energies 100 keV (green) and 300 keV (blue). Data plotted by the green line were multiplied by a factor of 3. Vertical black line indicates orientation of the OTR target.

EXPERIMENTAL SETUP

The experiment was performed using the electron source of the TRIUMF superconducting linear accelerator which is presently undergoing a commissioning phase. The accelerator is designed to generate high power electron beams with an energy up to 50 MeV and will be primarily used to produce radioactive ion beams via photofission for the ARIEL (Advanced Rare IsotopE Laboratory) facility [5].

The electron source allows CW and pulsed beam operation up to an average current of 10 mA. The main components of the source are a gridded dispenser cathode in a SF_6 filled vessel, and an in-air high voltage power supply. Unique features of the gun are its cathode/anode geometry to reduce field emission, and transmission of RF modulation via a dielectric (ceramic) waveguide through the SF6. The beam can be modulated by applying a superposition of DC and RF voltages to the grid. In order to match the beam to the accelerator structure, the electron source provides electron bunches with a charge up to 15.4 pC at a repetition frequency of 650 MHz, a subharmonic of the linac operating frequency of 1300 MHz. Additionally, the duty factor of operation can be changed between 0.1% -100 % by superimposing a macro-pulse structure at Hz to kHz frequency.

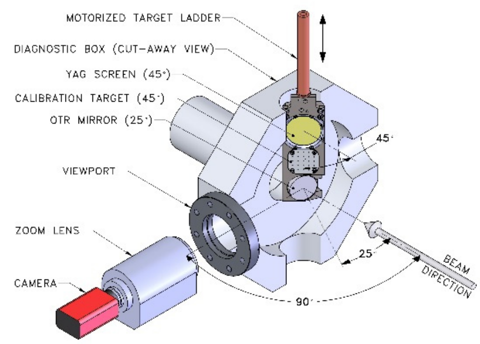

Figure 3: The experimental setup for OTR low energy imaging.

According to beam dynamic simulations the minimum energy required for the direct injection of the beam into a 9-cell SC accelerator is 250 keV. The energy of the source is varied by High Voltage applied to the anode of the gun up to a maximum value of 300 kV.

The OTR measurements were performed using a profile monitor located ~2 m downstream of the electron source. The OTR target was mounted on a motorized actuator with its normal oriented at 25° with respect to the beam direction. The target was a commercial 9.5 mm thick aluminium mirror with a diameter of 38 mm. In addition, a YAG scintillator and a camera calibration target were mounted at 45° on the same frame. The YAG screen was a 0.52 µm thick layer of P46 phosphor powder deposited on an aluminium substrate with a diameter of 50 mm. The camera, model GigE Manta G-032, was mounted at 90° with respect to the beam. It was equipped with a Computar motorized zoom lens, model H10Z1218. The camera features an adjustable gain and minimum exposure time of 26 µsec.

RESULTS

The chosen geometry of the measurements helped to mitigate the problem of the blackbody light emitted from the thermionic source. In fact the blackbody radiation was reflected by the mirror away from the camera. Still some light scattered from the target frame could be observed. It turned out that optimal regime for the measurements was operating the source with millisecond-range long pulses repeated at 50 Hz with a peak beam current around 100 µA. The beam current was kept low to minimize damage to the OTR mirror, a concern that eventually turned out to be unjustified. No signs of damage on the mirror surface were observed upon completion of the experiment.

Beam images were measured at two beam energies of 300 keV and 100 keV with both OTR and YAG screens to compare the results obtained by different techniques. The camera gain and beam pulse length were adjusted to accommodate the difference in the light intensity from two screens and to avoid saturation effects. To observe the OTR with a minimum amount of beam the camera gain was set in the range 30-36, while for the YAG phosphor it

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was at the minimum value of 0. It was found that to obtain a usable beam image, at least 150 nC of beam charge was required at 300 keV and about 400 nC for 100 keV beam. Processing of OTR images required measuring and subtracting the background. For YAG screen images the background level was negligible. Raw OTR images after the background subtraction are shown in Fig. 4a and Fig. 6a.

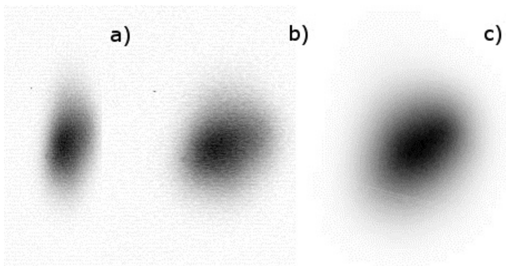

Figure 4: Raw OTR image (a), OTR image transformed to the beam coordinate space (b), YAG image (c). Beam energy is 300 keV.

Due to the target tilt by the angle ψ, coordinates in the image space relate to the beam space coordinates as

$$\begin{pmatrix}x_b\\ y_b\end{pmatrix} = \begin{pmatrix}1/\tan\psi & 0\\ 0 & 1\end{pmatrix}\begin{pmatrix}x_i\\ y_i\end{pmatrix} \quad (5)$$

OTR images transformed according to Eq. (5) are shown in Fig. 4b and Fig. 6b. For YAG screen $\psi = 45°$ and image coordinates are the same as beam coordinates. No image transformation is required in this case. YAG screen beam images are present in Fig. 4c and Fig. 6c.

Both OTR and YAG images look very much alike including a tilt of the beam elliptical shape. For quantitative comparison of beam sizes, horizontal and vertical profiles were obtained from the images and are shown in Fig. 5 and Fig. 7 for the beam energies of 300 keV and 100 keV, respectively.

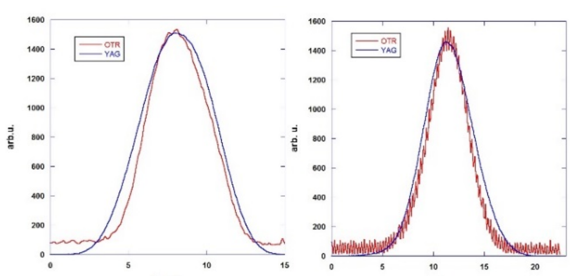

Figure 5: Horizontal and vertical beam profiles obtained from OTR and YAG images. Beam energy is 300 keV.

It can be seen that the OTR vertical profiles look much noisier. We believe that this is a feature of the camera (or a CCD sensor) manifesting itself in a slightly different amount of signal in odd and even lines of the image. The effect is only observable at high camera gains and gradually fades out as the gain is reduced.

Vertical and horizontal beam sizes were then calculated by applying the Gaussian fit to the beam profiles. For

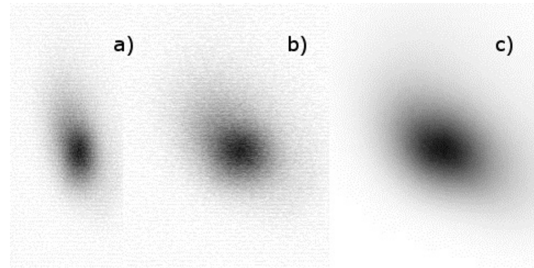

Figure 6: Raw OTR image (a), OTR image transformed to the beam coordinate space (b), YAG image (c). Beam energy is 100 keV.

OTR, both horizontal and vertical 1-σ beam sizes were the same amounting to 2.7 mm and 3 mm for 300 keV and 100 keV cases, respectively. For the YAG, all beam sizes were about 3.4 mm for both beam energies.

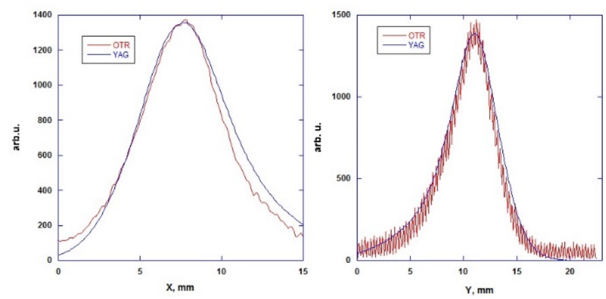

Figure 7: Horizontal and vertical beam profiles obtained from OTR and YAG images. Beam energy is 100 keV.

Taking into account that OTR and YAG measurements were performed with substantially different beam pulse lengths we conclude that the agreement between the two techniques is acceptably good. This result suggests that OTR can confidently complement the YAG beam imaging at the source energies of the TRIUMF electron linac with an obvious benefit of tolerating much higher beam powers than phosphor screens.

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