EXPERIMENTAL INVESTIGATIONS ON GEOMETRICAL RESOLUTION OF ELECTRON BEAM PROFILES GIVEN BY OTR IN THE GeV ENERGY RANGE.

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1 ABSTRACT

Optical Transition Radiation (OTR) provides an attractive method for diagnostics on beams of small dimensions at high energies (GeV). However, some limits on the geometrical resolution at very high energies, have been often discussed in the literature and a minimum value given by $\lambda\gamma$ has been conjectured. In order to bring an experimental contribution to the problem, systematic measurements of electron beam profiles, in the energy range 1 - 2 GeV and optical wavelength range 400 - 700 nm, have been worked out at the Orsay Linear Accelerator. OTR emitted from an Aluminium foil at a 30° incidence angle was collected by a two-lens telescope and recorded by an intensified CCD camera. The beam profiles measured with OTR were compared to profiles obtained with an SEM Grid having a resolution better than 0.5 mm and placed close to the OTR radiator. The results clearly show that the OTR geometrical resolution at GeV electron energies is better than the often invoked $\lambda\gamma$ limit.

2 INTRODUCTION

The angular distribution of transition radiation on a metallic surface is peaked on a half cone-aperture $\theta = 1/\gamma$ around the electron velocity (forward radiation) or around the direction of specular reflection (backward transition radiation; $\gamma = E/m >> 1$). The angular radius at half maximum is about 2.4 times larger. Concerning the application of transition radiation to measurements of beam profiles, it has been suggested that the narrowing of this peak at increasing γ will spoil the resolution of the beam profile, due to the diffraction effect. In fact, for a light beam of divergence $\Delta\theta$, diffraction imposes a minimum resolution for the transverse profile of the source: $\Delta b \geq \lambda/(4\pi\Delta\theta)$ where λ is the optical wavelength employed.

Setting $\Delta\theta \sim 1/\gamma$ results in: $\Delta b \sim \gamma\lambda/(4\pi)$. At $\gamma \sim 10^5$, the resolution would be ~ 1cm.

This prediction can be doubted; in fact, the angular distribution has a long tail which decreases only as θ^{-2} and the largest part of transition radiation is actually emitted in this tail. One could choose

$$\Delta\theta = \sqrt{\left\langle \theta^2 \right\rangle}$$

instead of $1/\gamma$ to calculate the diffraction effect.

From

$$I(\theta) \propto \left(\frac{\theta}{\theta^2 + \gamma^{-2}} \right)^2 \text{ one finds}$$

$$\sqrt{\left\langle \theta^2 \right\rangle} \approx \theta_{max} \frac{1}{\sqrt{\left[2 \ln\left(\gamma\,\theta_{max} \right) \right]}}$$

where θ_{max} is the angular acceptance of the optical system, which is assumed to be much larger than $1/\gamma$. Thus, the resolution would not be much worse than the intrinsic one of the optical system $\Delta b \sim \lambda/(2\pi\theta_{max})$ and would deteriorate very slowly when γ increases. Similar conclusions have been obtained in Refs. [1,2].

This question has been a subject of controversy since others have emphasized the influence of the $\lambda\gamma$ factor on the resolution [3,4]. Up to now, very few experiments have been undertaken to elucidate the resolution problem. One of us (L.Wartski) has observed electron beam dimensions of about 1mm at 1 GeV [5]. In order to investigate this question, we have realised an experimental test at the 2 GeV Orsay Linac. The general interest to diagnose high energy beams of small dimensions in connection with the linear collider projects, is actually the motivation of this work.

3 DESCRIPTION OF THE EXPERIMENTAL SET - UP

The experimental set - up is installed on the front end of the Orsay 2 GeV Linear Accelerator (fig 1).

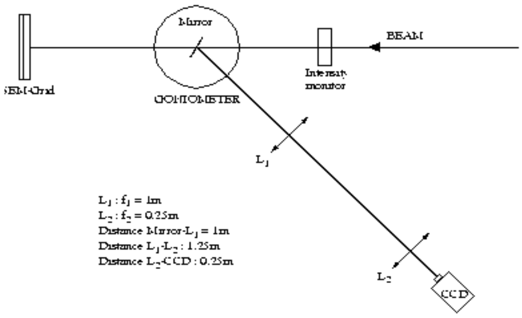

Fig 1. The experimental set-up

The OTR radiator is a 20 microns thick aluminium foil mounted inside a goniometer which allows precise angular orientations as well as complete removal. The electron beam impinges on the radiator with 30° incidence angle. The experimental set-up is shown in fig.1.
The beam intensity is monitored with a toroid placed upstream of the radiator. An SEM Grid providing horizontal and vertical beam profiles with a 0.5 mm resolution is placed downstream of the goniometer.
Requirements for small emittance beams, so as to obtain small beam dimensions, is realised using two collimators 60 meters apart; the closest one is placed 40 meters upstream of the radiator. Beam aperture, at their location, is restricted to 2X2 mm^2. A quadrupole doublet, 30 meters upstream of the radiator, permits beam focusing.
The beam energy is varied from 1 up to 2 GeV and the beam charge from $1 \cdot 10^{10}$ to $2 \cdot 10^{10}$ e^-/pulse for a 30 ns pulse width.
The OTR beam image is transmitted through a glass window (BK 7) to the optical channel made by two lenses (f1 = 1m, f2 = 25 cm) mounted in telescopic configuration (M = 1/4).
An intensified CCD camera is placed at the focal plane of the second lens. Optical interferential filters in the range 400 - 800 nm, with 40 nm FWHM bandwith value, are used. Alignment of the optics is provided using a He-Ne Laser.
Prior to each experimental session a control of the general alignment is performed by observing the image of the thermoionic cathode on the CCD.

4 OPTICAL SYSTEM ANALYSIS

Experimental calibrations have been worked out in order to determine the precise ratio mm/pixel on the CCD. This was done using a small monochromatic source which was shifted by a step by step translator with 1 micron accuracy.
The calibration results provided ratios of 0.097 mm/px and 0.064 mm/px for the horizontal and vertical direction respectively. Estimations of the error on the magnification resulting from the radiator inclination and contribution from spherical or chromatic aberrations showed almost negligible values. Hence the relative error due to the optics elements may be neglected. This situation is due to the high directivity of the radiation and to an accurate alignment of the optical sytstem.

5 MEASUREMENTS

The experimental observations were focused on the variation of three parameters: the electron beam energy, the optical wavelength, and the camera gain (voltage level of the intensifier).
Two beam energies were selected: 1.1 and 2.0 GeV, corresponding to the maximum linac energy.
For a given energy, observations were related to the whole optical spectrum or to a selected optical wavelength. A home made image acquisition and analysis code enabled us to get the transverse profiles from the images and to derive the 90% and FWHM intensity widths.

5.1 Measurements at 2 GeV

Observation at 2 GeV showed almost gaussian profiles, even for measurements carried out under low sensivity conditions. Examples are presented in fig. 2 and 3 corresponding to the whole optical spectrum and a restricted zone (around 500 nm) respectively.

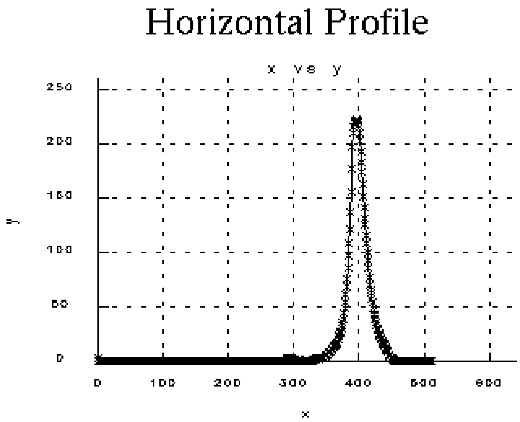

Fig. 2. Beam profile for the whole optical spectrum. Camera gain = 35.

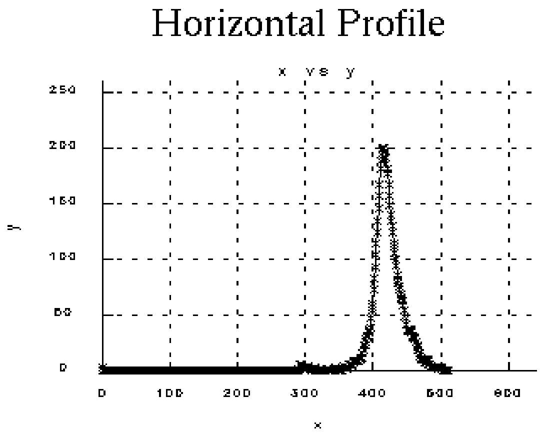

Fig. 3. Beam profile for 500nm wavelength.
Camera gain = 125.

The CCD gain is indicated. The beam size was controlled for each measurement set by means of the SEM Grid placed downstream of the OTR radiator. TRANSPORT and TURTLE code [6] simulations demonstrated that the differences between the two measurement positions did not entail substantial variations.
1) For a fixed gain value of the intensified camera we carried out a series of measurements for different optical wavelengths. We observe a correlation between the measured beam widths and the camera sensitivity. This is shown in fig.4 where the spectral response of the intensified CCD camera and the beam widths gathered at a fixed gain level are superimposed. The vertical scale, in

mm, is such that the maximum width (corresponding to 500nm) lies on the sensitivity curve.

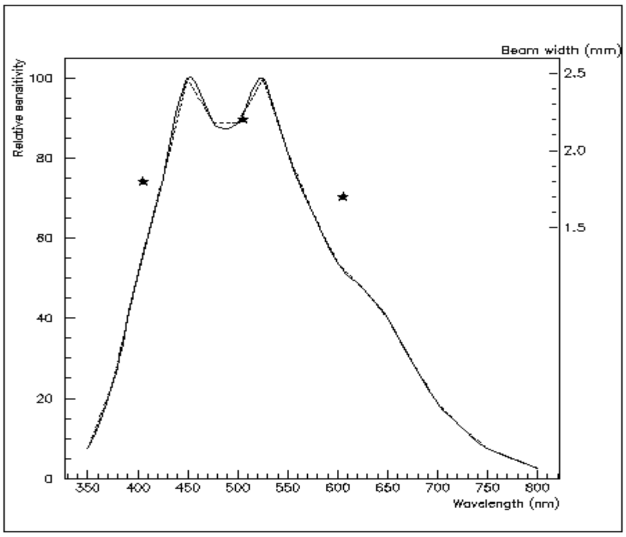

Fig. 4. Spectral response of the intensified camera. The experimental measured widths are superimposed.

Analogous observations can be stated for differents gain levels. The dependence of the measured beam widths with the wavelength is mainly related to the spectral behaviour of the intensified camera.

2)At fixed wavelengths, systematic measurements were undertaken to test the dependence of the measured widths with the intensified camera gain.

For every wavelength we determined a minimum gain needed to obtain a beam image and a maximum gain for which the camera went into protection. The range of gain variations extended up to 160 (normalised scale). For each wavelength, an optimum gain has been determined. It corresponds to the gain value for which the number of pixels concerned by the filtered image (i.e. the FWHM) is the same as for the whole spectrum image at minimum gain. The variations of the beam image FWHM with respect to the camera gain exhibits a logarithmic behaviour. Comparing, for the same beam settings, the profiles obtained with different camera gains, we notice that they conserve a gaussian shape and that the ratio between the FWHM and the 90% intensity width is conserved throughout the total variation of the gain.

5.2 Behaviour of the beam width with the electron energy

The behaviour of the OTR images with different electron energies has also been examined. Comparisons have been made with measurements at 1.1 GeV for the same beam optics as for 2 GeV.

We notice that:

- at a given wavelength and for the same camera gain, there is no significant beam image enlargement when increasing the energy from 1.1 to 2 GeV (as refering to the widths measured at the SEM Grid)

- For the same FWHM value we do not observe any significant and systematic enlargement of the 90% intensity width value. This fact could be related to the absence of a "halo effect".

-at 2 GeV and observing in the red part of the spectrum (700nm) the FWHM value is about 1.7 mm. That is well below the $\lambda\gamma$ estimation of 2.8 mm.

6 SUMMARY AND CONCLUSIONS

The series of measurements performed at 1.1 and 2 GeV have shown that:

1) the main contribution of the wavelength in the measured widths is determined by the camera spectral sensitivity.

2) most of the variations of the beam size observed on the CCD, for the same width given by the SEM Grid, are related to the overall efficency of the camera.

3) no evident dependence of the beam width with the electron energy has been noticed. The gaussian like shape of the beam profile is fully conserved and comparable widths, for the same beam optics, are observed for an energy scale of almost a factor 2. No halo is observed, for the same beam optics, when increasing the beam energy from 1.1 to 2 GeV.

In conclusion we can infer from our measurements that, in the energy range considered, we have not noticed any resolution limit associated to the $\lambda\gamma$ value. Such investigations will be continued at intermediate energies and with smaller beam sizes.

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