ELECTRON BEAM TRANSVERSE EMITTANCE MEASUREMENT USING OPTICAL TRANSITION RADIATION INTERFEROMETRY

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Abstract

We report on measurements of the ELSA electron beam transverse emittance obtained by exploiting the optical transition radiation (OTR) properties. The experiments were achieved with a beam of 10-20 ps bunch duration, 0.2 to 3 nC/ bunch charge and 16.5 MeV energy. Beam profile and OTR light angular distribution were measured in successive sequences by means of an interferometer, which consists of an 8-µm Kapton foil followed by a 80-µm Si wafer used as a mirror; the spacing between foils is 1.06 mm. Beam divergence is obtained from a least squares fitting of the interference-pattern data with an OTR distribution function in which the varying parameters are the beam energy and the angular spread. This technique yields the transverse emittance, provided that the measured profile corresponds to a beam waist. Concurrently, measurements using both the quad-scan technique and the single OTR foil method have been performed. Results obtained by the three methods are presented and their performances discussed.

1 INTRODUCTION

The optical transition radiation (OTR), which is produced when a charged particle crosses the interface between two media of different permittivities, has been investigated for many decades. Since the pioneering studies of Wartski [1], works have been extended to high-brightness electron linacs in the late 80's [2]. The OTR is well adapted to detect and monitor electron beams along their transport. Moreover, the intrinsic properties of this process, i.e. fast response (of the order of the picosecond), and angular distribution dependence with beam caracteristics, make the OTR very attractive as temporal and spatial beam diagnostics.

We present an experimental technique based on OTR properties for measuring the electron-beam emittance on our ELSA linac. Measurements based on the single-foil method and two-foil interferometry are described. We report also on emittance measurements using the "quad-scan" method, extensively used in our laboratory [3]. In this method, which is time consuming, beam profile is measured for at least three different values of the current in a quadupole placed ahead of an OTR screen. Results obtained with the three techniques are compared and respective performances are discussed.

2 OTR-BASED EMITTANCE MEASUREMENTS

Beam transverse emittance at a waist is given by the following expression :

$$\varepsilon_i = 4\,\beta\,\gamma\,[\,\langle x_i^2\rangle_w\,\langle\sigma_i^2\rangle_w]^{1/2} \qquad (1)$$

with :

- ε_i : emittance (i : horizontal or vertical direction),
- β, γ : particle reduced velocity and Lorentz factor,
- $\langle x_i^2\rangle_w$: 2nd order moment of the beam transverse distribution,
- $\langle\sigma_i^2\rangle_w$: 2nd order moment of the beam angular spread.

This expression shows that the emittance is entirely determined if we can measure, on a single OTR screen, the beam profile and the angular spread successively or, better, simultaneously. Beam-profile measurement is straightforward using a video camera. Beam angular spread is estimated from the light emission pattern using the OTR angular properties. Limitations to this measuring technique can occur when the beam mean angular divergence is small compared to the inverse Lorentz factor. This means that if we cannot strongly focus the beam on the OTR screen, the single-foil technique is difficult to use.

An alternative to the single-foil technique is the two OTR source interferometry, first studied and developed by Wartski 20 years ago [1]. In this method, two foils are used, forming two coherent light sources, the second foil acting also as a mirror for the first source. The interferometry pattern allows to derive lower beam angular divergence even at moderate energy.

3 EXPERIMENTAL SET-UP

3.1 The ELSA linac

The ELSA electron linac has been previously described [4]. Only features characteristic of the present experiment are given here. The accelerator is composed of a 2-MeV photoinjector RF cavity followed by three cavities accelerating the beam up to 16.5 MeV. The beam consists of a 50-µs macropulse train at 1 Hz repetition rate. Each macropulse contains micropulses of

20-ps duration at 14.44 MHz repetition rate. In order to study beam dynamics and to improve the accelerator performances, it is necessary to precisely measure the beam brightness, that is, peak current and transverse emittance. The photoinjector has an anode coil of particular importance since it counteracts the beam space-charge and the RF defocusing effects which are important at low electron energy. The influence of the anode-coil magnetic field on beam qualities is investigated here for extracted charges ranging from 0.2 to 3 nC per micropulse.

3.2 OTR angular distribution observation

Emittance measurements are made at the exit of the linac, where an OTR screen is placed. It serves for the quad-scan and OTR-based techniques. In the quad-scan method, the current of a quadrupole, located ~1.5 m ahead of the OTR target, is varied and corresponding beam profile is measured [3]. In the OTR-based method, angular and spatial distributions are observed with an experimental set-up, displayed in Fig. 1 and devoted to OTR studies [5].

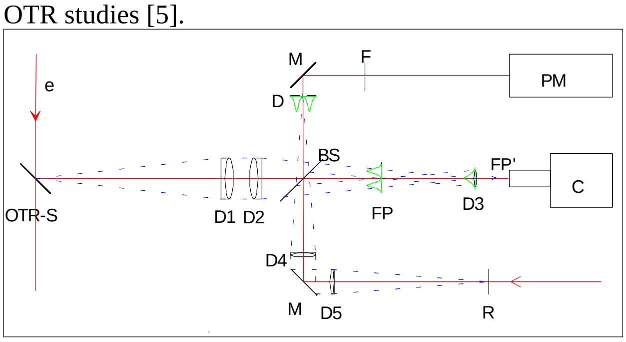

Figure 1: Layout of the setup for OTR angular- and spatial-distribution measurements.

A camera (C) moves along the optical axis to observe either the focal plane (FP) of an achromatic doublet D1-D2 to yield the angular distribution, or the image plane (FP') of the doublet D3 to give the spatial distribution (Fig.1). The video signal of this camera is digitized through an image processing device composed of a Sofretec PITER 500 frame grabber, a 486 DX PC and a TV monitor. Each image is digitized with 256 possible gray levels and stored in a 512 × 512 bytes memory. Images are processed off-line using a code developed in FORTRAN language on a SUN workstation.

3.3 The interferometer

The two-foil interferometer consists of an 8-µm Kapton foil followed by a 80-µm-thick silicon wafer optically polished. The foil spacing has been measured after the experiment and is 1.065 ± 0.010mm. The OTR spectrum is filtered with an ANDOVER bandpass filter centered on 650.9 nm with a FWHM bandwith of 35.3 nm. This ensures exploitable interference pattern.

4 DATA ACQUISITION

Measurements have been taken with the three techniques, on a 16.5-MeV, 20-ps bunch length, 50-µs macropulse duration electron beam, with bunch charges of 0.2, 0.5, 1.0, 2.0, and 3.0 nC. For each bunch charge, measurements were performed for 4 values of the anode coil field: 1.6, 1.7, 1.8 and 1.9 kGs.
The following experimental procedure has been adopted:

- in the quad-scan method, images are taken with, at least, 3 different values (6 - 7 values are usually taken) of the quadrupole field. The 2nd order moments are extracted from these images. In this method, it is assumed that the beam emittance is conserved in the transport from the quadrupole to the OTR screen.
- in the OTR-based techniques, the beam is ajusted to a waist on the screen by varying the current of the quadrupole located ahead. The beam spot size is then minimized, but the beam waist is in fact behind the screen [4]. Beam profile image is taken first, the camera is then moved to record the radiation angular distribution.

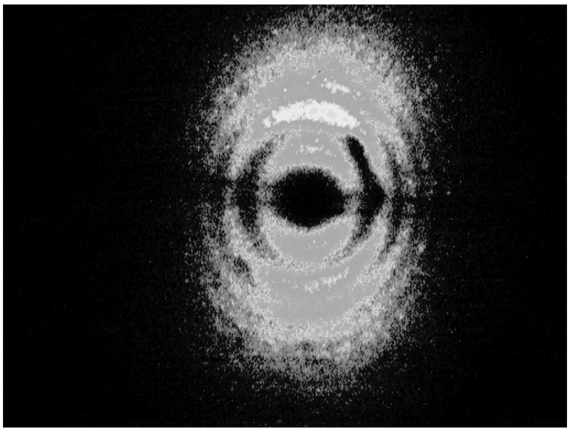

Figure 2: OTR interference pattern. The electron beam energy is 16.5 MeV, bunch charge is 5 nC and anode-coil field is 1.8 kGs.

In each measurement, a set of 5 images is recorded and analyzed, in order to reduce statistical fluctuations. An example of angular distribution obtained with the interferometer is given in Fig.2. In this figure, the OTR angular distribution appears to be strongly polarized in one direction; this is due to the crystalline nature of the silicon wafer.

5 MEASUREMENT RESULTS AND DATA ANALYSIS

Second order moments of the spatial distribution are obtained by analysing beam profiles in the two transverse directions (horizontal and vertical). Moments of the beam angular spread are deduced from the cross sections of the experimental OTR angular patterns. They are then introduced in a FORTRAN routine which automatically yields the maxima and minima of the curves. Position analysis of these extrema gives a rough estimate of the beam energy. The program is linked to a CERN library which offers the possibility to use the MINUIT computer code. This improved routine minimizes the χ^2 function for beam energy and mean angular spread simultaneously. The fitting function is the analytical solution of the OTR single-foil or interferometry processes. The program returns optimized parameters and the associated error matrix. The experimental data points and the corresponding optimized analytical curve for an extracted charge of 3.0 nC and an anode-coil field of 1.7 kGs are shown in Fig. 3. A good agreement can be noticed around the centre of the pattern. On the edges, the data points lie below the analytic curve, because of a limited acceptance angle of the optical system. Position and amplitude of the experimental extrema are well reproduced by the analytic curve. The 2nd order moments resulting from the fits are used in expression (1) to derive the normalized beam transverse emittance.

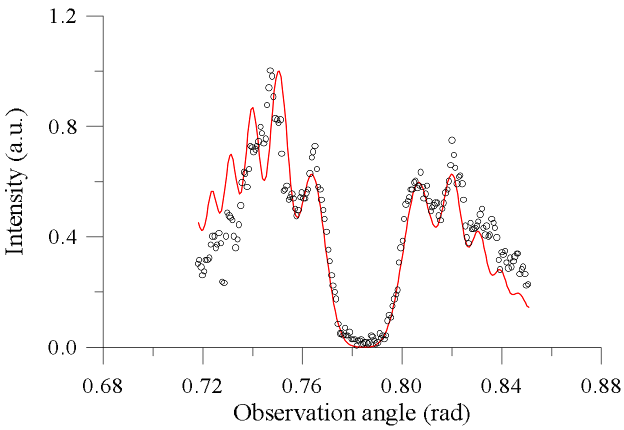

Figure 3: Vertical cross-section of the experimental angular distribution (open circles) for 3 nC/ bunch charge and 1.7 kGs anode-coil field. The full curve is a fit of the measured data.

Variations of the emittance, obtained with the three methods are displayed in Fig. 4 versus bunch charge. At each charge, the anode-coil field has been adjusted to minimize the transverse emittance. Beam emittance increases by, at least, a factor of two with charge going from 0.2 to 2.0 nC/ bunch, whatever the measurement method is. This behaviour is explained by the space-charge effect on the beam.

Discrepancies between the OTR-based techniques and the quad-scan method occur for all extracted charges. It appears that all the OTR-based techniques yield an overestimated emittance. The deviations are mainly due to the beam angular spread which is always larger than that given by numerical simulations. Two explanations can be given; first, the Coulomb scattering effect of the first transparent foil is presently not taken into account in our numerical analysis. This means that the angular spread created by the first foil is analysed as a natural beam divergence; second, in the OTR-based techniques, it is assumed that the beam is located at a waist, and that the coupling between spatial and angular variables is set to zero as shows expression (1). In fact when we get the lowest beam size on the screen, the beam waist is localized downstream this screen and coupling is non-zero. The deduced emittance always appears greater than it is in fact. For future experiments, we plan to improve our experimental technique in order to reduce the uncertainty on the beam-waist position and to obtain beam angular spread measurements with better accuracy.

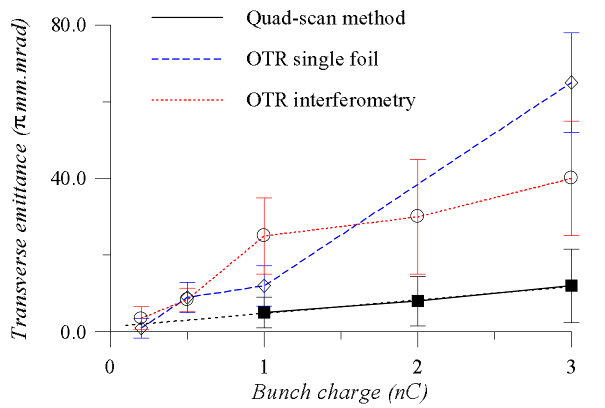

Figure 4: Comparison of beam transverse emittance measurements versus bunch charge, with the 3 different methods described in the text.

6 CONCLUSION

The OTR-based emittance-measurement techniques are very attractive and powerful, essentially the interferometry method. Contrary to the quad-scan technique, they are fast, since they need single measurements of the beam spot and the angular OTR angular distribution pattern. However, one needs to know precisely the beam spot size at the location of the waist and, in the interferometry method, the geometry of the interferometer (angle of incidence, parallelism of the two source foils, spacing between foils). One need also to improve the sensitivity of the beam mean angular measurement.

ACKNOWLEDGMENTS

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