6-D ELECTRON BEAM CHARACTERISATION USING OPTICAL TRANSITION RADIATION AND COHERENT DIFFRACTION RADIATION

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Abstract

The development of non-intercepting diagnostics for high charge density and high energy electron beams is one of the main challenge of beam instrumentation.

Diffraction Radiation based diagnostics, being non-intercepting, are among the possible candidates for the measurements of beam properties for the new generation linacs.

At the 1 GeV Sincrotrone Trieste linac, we are performing the first measurements of beam transverse parameters using Diffraction Radiation emitted by the electron beam passing through a 1 mm slit opened on a screen made of aluminium deposited on a silicon substrate.

The analysis of the angular distribution of the Diffraction Radiation for a given wavelength, slit aperture and beam energy gives information about the beam size and its angular divergence.

1 INTRODUCTION

The usefulness of Optical Transition Radiation (OTR) for electron beam diagnostics was demonstrated in 1975 by L. Wartski [1], but it took more than ten years before becoming a real instrument usable for beam measurement [2]. For the first time, in the design of the TESLA Test Facility (TTF) linac, OTR was considered as the main beam diagnostics tool, with the intent of fully exploit its many properties. In these years, we have used OTR to measure all the 6D phase space beam parameters. Some of the most interesting measurements will be described in this paper. More recently we started some experiments with the Diffraction Radiation (DR), that is emitted when the beam crosses a hole in a metallic screen. This radiation open the possibility of a non-intercepting diagnostics, required for high power beams or strongly focalised ones, as those designed for short wavelength FELs or Linear Colliders. On the TTF beam we have proved that coherent DR can give the same result as coherent Transition Radiation for bunch length measurement, while on the Sincrotrone Trieste linac an experiment is running to demonstrate the possibility of measuring beam size and angular spread with near-infrared DR.

Transition Radiation has many advantages over more traditional imaging devices, being completely linear and free from source saturation, but its spatial resolution has some peculiar aspects that can create some limits in the details that can be extracted from an image. So a very brief presentation of the space resolution of OTR will precede the illustration of the experimental results.

2 OTR RESOLUTION

Few years ago, some concern aroused about the spatial resolution reachable with OTR, especially at very high energy. The reason was the collimating of the radiation, with its peak cone at an angle of $1/\gamma$, that could produce an auto-diffraction limit increasing with the energy. This argument has been fully studied in [3-5], and now we know that the only real limitation arises from the collection optics diffraction, independently from energy, but with peculiar features due to the nature of this radiation. In particular, the radial polarisation produces a zero in the centre of the image, resulting in a FWHM larger than that of a standard scalar point source. On the other hand, the extension of the source (the e.m. field of the particle) increases with energy, and this produces a long tail which contain most of the optical intensity. This means that some caution must be used in defining the OTR spatial resolution, depending on how this long tail is managed. Figure 1, taken from Ref. [4], shows the normalised radial distribution for a single particle OTR image with different angular acceptance.
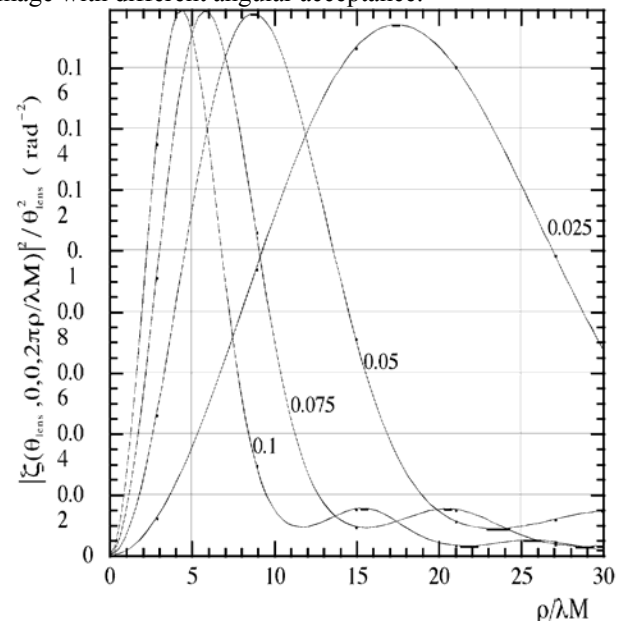

Figure 1: Normalised OTR angular distribution for different acceptance of the collection optics.

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The 3D image is shown in Figure 2, together with its projection on one axis. The tail has been cut at the 0.5% of the maximum.
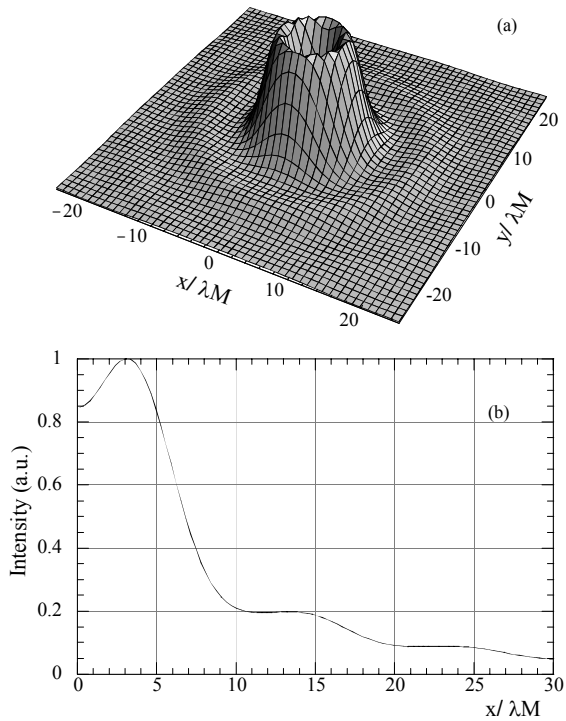

Fig. 2 – 3D OTR distribution and its projection on a plane. Tails are cut at .5% of the peak intensity
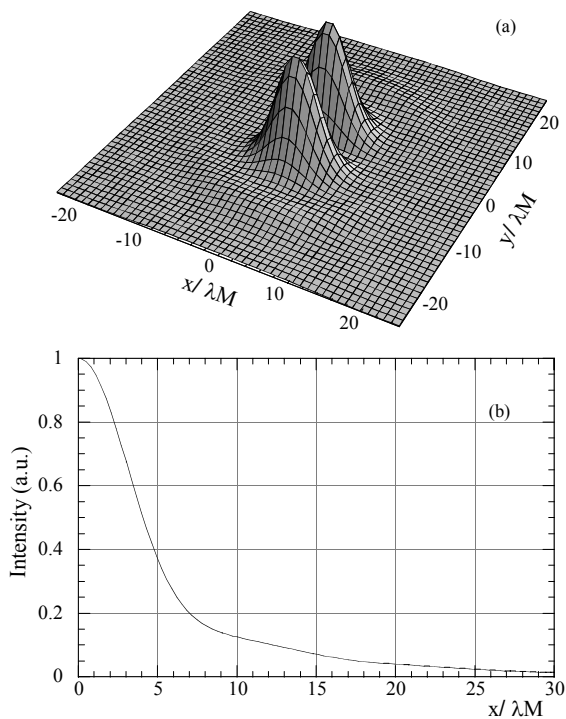

Fig. 3 – 3D OTR selected by a polarizer and its projection on the plane normal to the polarisation vector

From this picture it is possible to see that the FWHM is of the order of 12 λ, i.e. much larger than a standard point source with the same angular acceptance.

A better resolution can be obtained by the use of a polarizer. In this case, as shown in Figure 3, a FWHM of about 6 λ can be reached.

3 OTR MEASUREMENTS

In this paragraph we will illustrate some of the measurements performed on TTF. We will not mention the more standard measures, as the emittance measurement by the quadrupole scan or the beam size evolution along the macropulse taken by a gated camera, that were already presented at a previous Conference [3]. Instead, we will give space to measurements where the image details are important.

3.1 Pepper Pot measurement

At the injector level we have a beam of 16 MeV, and with a charge per microbunch of 1-4 nC, the standard emittance measurement by quadrupole scanning is rather inaccurate, requiring a space charge effect correction, which is by necessity based on not well known beam parameters. We are routinely using a pepper pot technique. The beam passes through a system of 100 μm wide slits cut in 1 mm stainless steel target. Two sets of slit are present: with .5 mm and 1 mm spacing. An OTR screen, at 45 degree, is mounted on the same actuator allowing the beam dimension being measured. The beamlet sizes and relative positions are measured on an OTR screen some 60 cm downstream.

Fig. 4 – OTR image of the beam through the slits

Figures 4 show a typical OTR image of the beam through the slits. From the projection on the horizontal axis the emittance is derived on-line (figure 5).

This technique is fast enough to allow the optimisation of the gun and capture section settings.

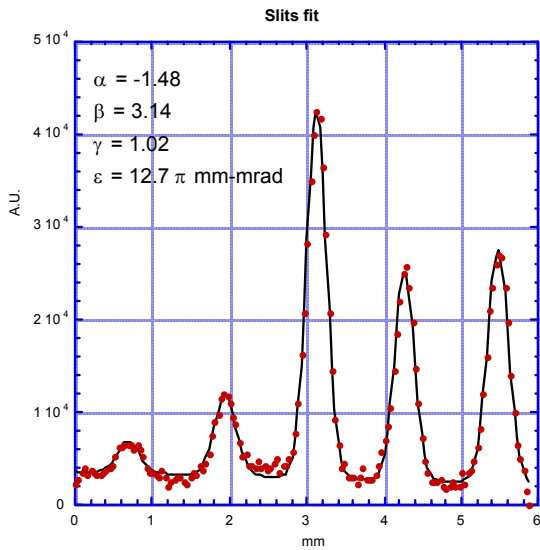In this case the advantage of OTR over other fluorescent screen is its absolute linearity.

Fig. 5 - Emittance reconstruction from the slit image

3.2 Longitudinal phase space tomography

Measuring the energy spread in a dispersive section after a bending magnet by means of OTR is not often considered necessary or even advantageous. The reason is that in this case the beam is spread over a rather large surface, giving a very low OTR intensity, and in many cases small details are not considered important. There are also effects, in using OTR for imaging large objects, that must be carefully evaluated and considered in the design stage. One of the main problem is the possible different radiation collection efficiency from the centre or the border of the image. To evaluate this effect and design an appropriate optical system, it must be remembered that it is true that OTR has a peak at an angle of $1/\gamma$, but most of the intensity is carried by the tail at much larger angles.
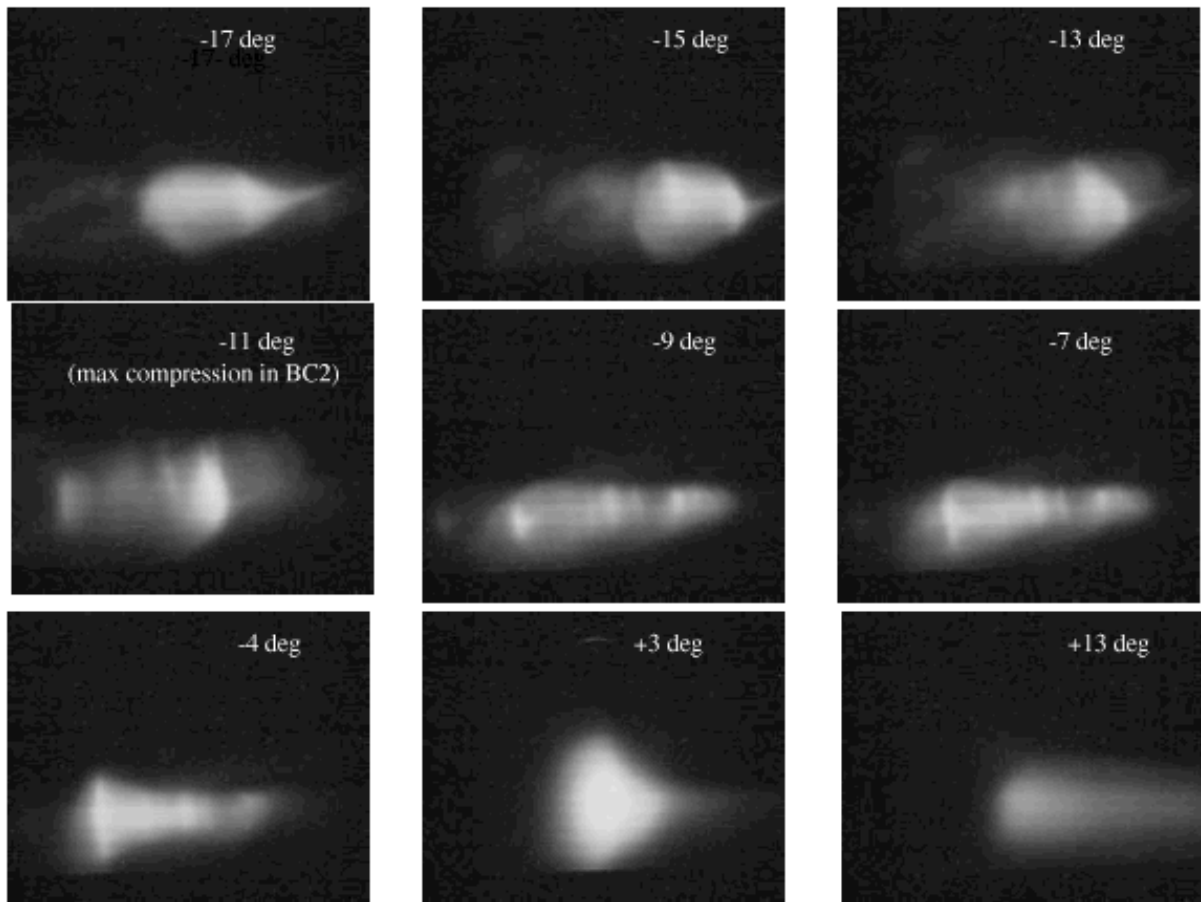

Fig. 6 - Energy spread at the end of the TTF linac as function of the off-phase angle in the first accelerating module

There are measurements for which the details that only OTR can give are absolutely required. One of these is the tomographic reconstruction of the longitudinal phase space.

To reduce the bunch length and increase the peak current for the FEL experiment, in TTF there is a magnetic compressor after the first accelerating module. Driving the beam off-crest in this module, a correlated energy spread is introduced, and the compressor rotates

the longitudinal phase space, resulting in a shorter bunch. This process introduces unwanted, and not completely predicted, energy modulations. To study this effect, a measure of the energy spread at the end of the linac for different compression factors can be used for a tomographic reconstruction of the longitudinal phase space. In Figure 6 the measured energy spread for different phases in the first module, corresponding to different compression values, is shown.

More information can be found in the talk of M. Hüning at this conference [4].

3.3 Energy stability along the macrobunch

A more traditional use of OTR is the measurement of its angular distribution, of which an example is shown in Figure 7. From a line profile through the centre of this image, the beam energy and angular spread can be obtained
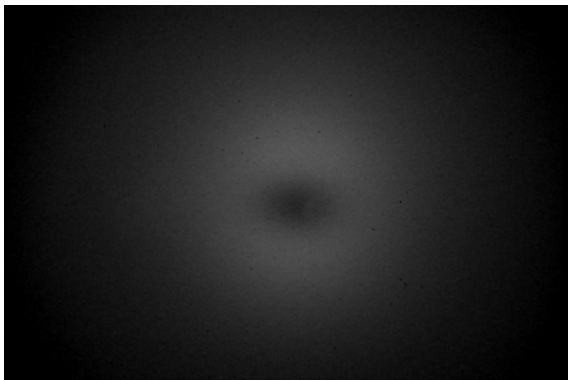

Fig. 7 - OTR angular distribution

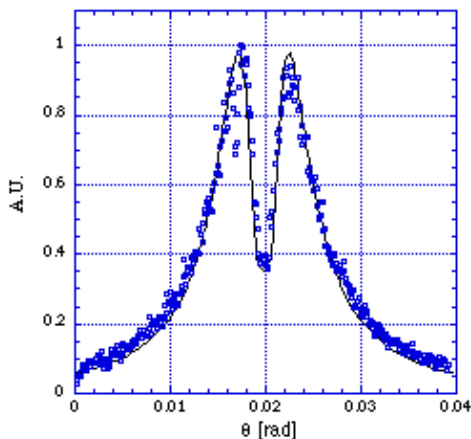In Figure 8 is shown the line profile obtained from the previous image.

Fig. 8 – OTR angular distribution profile with a fit giving beam energy and angular spread

Our main interest was in this case on the energy value, that is obtained in absence of any dispersive section, and

thus in any place along the linac. Using a gated camera, the energy for each single micropulse along the macropulse can be measured. Figure 9 show the result obtained at two different acceleration gradient during the set up of the RF feedback system.
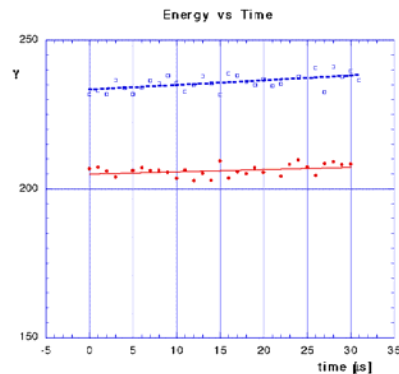

Fig. 9 - Energy stability along macropulse

4 DIFFRACTION RADIATION

OTR is very useful foe many aspects, as we have shown, but it is an intercepting device, directly hit by the beam. Like all intercepting devices, there is a limit in beam density that can be supported. For the new generation of beams for both Linear Colliders and FELs this limit is easily reached. A new generation of non-intercepting diagnostics is thus needed.

Diffraction Radiation (DR), i.e. the radiation produced when a particle goes through a hole or passes near the border of a screen, can be a possible solution. This radiation is only a special case of Transition Radiation, when only part of the e.m. field of the particle hits the screen, and diffraction aspects arise. For this to happen, the transverse extension $\lambda\gamma$ of the e.m. field of the particle must be larger than the hole radius

At the energy of less than 300 Mev, as actually available on TTF, the only way to exploit DR is through the coherent emission at wavelength equal or longer than the bunch length. It is well known that from the coherent spectrum it is possible to reconstruct the bunch length itself, and this technique has been widely used with transition or synchrotron radiation. We have used for the first time in a clear way the coherent DR.

For this experiment we have mounted a variable aperture slit, that allowed us to compare the intensity of DR with that of TR in the same experimental conditions.

The complete description of the experiment can be found in [5], here we will only show that to exactly evaluate the CDR spectrum, the effects of the finite dimension of the screen, analysed in [6], and the relatively short distance of the detector from the source that does not allow the use of asymptotic formulae, must be taken into account.

In Figure 10 the total CDR intensity as function of the slit aperture is shown together with the behaviour expected using the far field analytic expressions presented in [7] for a slit in an infinite screen.
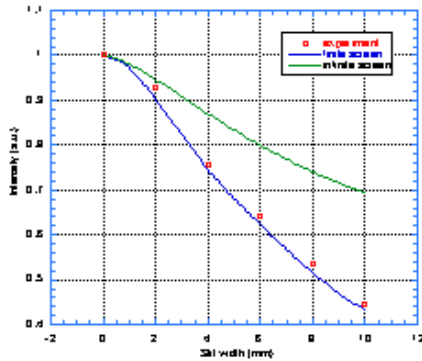

Fig. 10 – CDR total intensity as function of the slit aperture and theoretical curves based on different assumptions

It is evident that to account for the experimental results, a more realistic description, taking into account both the finite screen effect and the source dimension, is required.

The bunch length has been obtained from the interferograms in a simple way, assuming a single cut-off frequency, and the results, as function of the slit aperture, are shown in Figure 11.
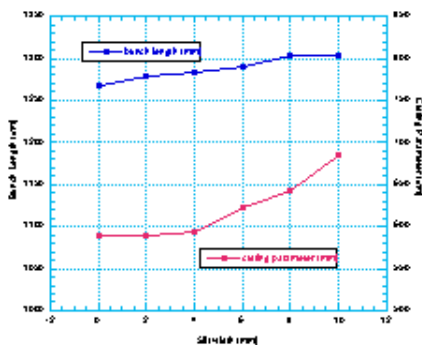

Fig. 11 – Bunch length and cutting frequency as function of slit aperture

We have demonstrated that CDR, even with rather large slit aperture, gives a bunch length equivalent, within the errors, to that obtained for CTR, but in a non-intercepting way.

Diffraction Radiation, at larger energies, gives also the possibility of measuring the beam size and angular distribution, as was suggested in [8].

An experiment is in progress at the 1 GeV linac of the Sincrotrone Trieste. In this case a fixed slit of 1 mm aperture is used, but the available energy requires to work with infrared radiation (1.6 mm) making the measurement much more difficult.
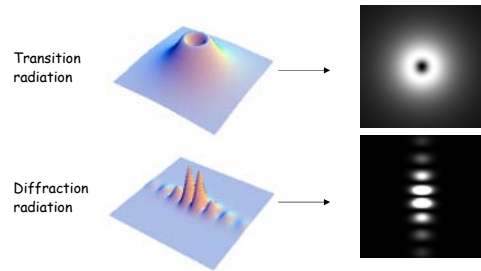
Comparison between TR and DR

Fig. 12 – TR and DR angular distribution

In Figure 12 is shown the difference between the angular distribution of OTR and that expected for DR. The fringes visibility is a function of the beam size.

We will also test the possibility of changing the relative phase of the two half plane, in order to modify the angular distribution of the radiation, as shown in Figure 13. Many interesting applications can be obtained by a clever use of the phase control.
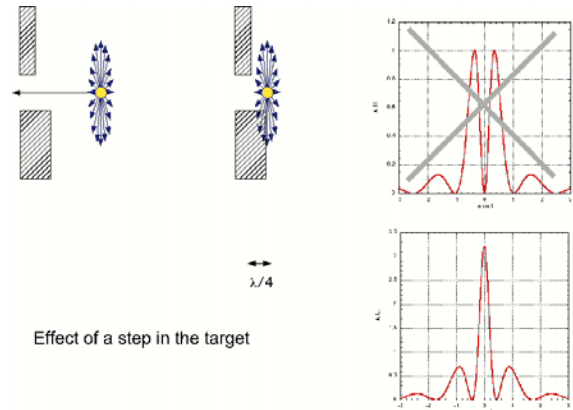

Fig. 13 – Effect of phase control in DR

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