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Analysis of optical transition radiation emitted by a 1 MeV electron beam and its possible use as diagnostic tool

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Abstract

The main features of optical transition radiation (OTR) backward emitted by a 1 MeV electron beam crossing a vacuum-to-metal boundary are presented. The possible use of OTR as a diagnostic tool for such a low energy beam is discussed, and some preliminary experimental data are presented.

1. Introduction

In its simplest form the transition radiation is emitted when a charge moving at a constant velocity crosses a boundary between two materials with different dielectric constant.

The possibility of such an emission was discovered rather late in the electromagnetic theory development [1] and considered of little practical interest.

The observation that for ultra relativistic particles the radiation emitted forward (along the motion direction) can appear in the UV or even X-ray spectral range with a total intensity proportional to the particle energy led to the development of the so called ''transition counters'' and greatly enhanced the interest for the effect.

Wartski first considered the transition radiation in the optical range (OTR) as a diagnostic tool for relativistic electron beams and, in the period between 1972 and 1975, demonstrated the possibility of measuring beam divergence and emittance through the detection of OTR radiation emitted by a single metallic surface or by a pair of metallic foils (OTR interferometer) [2,3], however, the relatively low current produced by linacs at that time, together with the low intensity of OTR, prevented the further development of the technique.

More recently, Rule and Fiorito developed a complete series of diagnostic instruments for the high peak current electron linac accelerators of the Los Alamos and Boeing FEL projects, also exploiting the possibility of time resolved measurements along the macropulse [4–7].

In the case of electron beams produced by superconducting linacs, the long macropulse, up to CW, easily compensates for the rather low microbunch charge, so that the intensity of OTR is sufficient for diagnostic purpose. The possibility of time resolved measurements is in this case of great importance, the time stability of the beam being one of the more significant advantages of superconducting linacs.

This is the main reason for our considering to make extensive use of OTR in the beam diagnostics of the 25 MeV superconducting linac LISA, to measure energy stability and emittance.

During the preliminary study of the diagnostic tools, we also considered the possibility of using OTR to analyse some of the parameters of the 1 MeV injector beam. In this paper we present the theoretical analysis of OTR emitted by 1 MeV electron beam crossing an aluminum screen, its possible use in the beam diagnostics and some preliminary experimental results.

2. OTR emitted by a 1 MeV electron crossing a vacuum–aluminum boundary

When a charge crosses a boundary between two different media, transition radiation is emitted both in the forward direction, along the particle motion, and backward. The spectral contents of the two radiations can be quite different depending on the dielectric properties of the media. Here we are concerned with radiation in the optical range emitted by an electron of rather low energy when

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crossing a vacuum-to-metal boundary. If the thickness of the metal target is larger than the electron range, there is no detectable forward emission at these frequencies, so that only the backward radiation can be measured.

For a beam in an accelerator environment this is usually accomplished by putting a target at 45° to the beam direction and measuring the backward radiation, emitted around the direction of specular reflection of the velocity vectors, through an optical window. Focussing the target on the sensor of a TV camera, the transverse distribution of the beam can be measured, the OTR intensity being strictly proportional to the incident total charge. On the contrary, focussing at infinity, it is possible to measure the angular distribution of OTR.

It is not in the purpose of this paper to discuss general properties of transition radiation, that can be found in previously referenced papers and in books [8,9]. General formulae for the radiation intensity emitted by a charged particle crossing a surface at an arbitrary angle have been derived by Pafomov and are summarized in Ref. [9]. These rather cumbersome formulae can be simplified in the case of a vacuum-to-metal transition.

For an ultrarelativistic particle ($\gamma \gg 1$, γ being the reduced particle energy) the radiation intensity can be derived from the simple model of a "real" charge and its "image" in the metal instantaneously annihilating at the boundary. In this approximation the metal can be considered a perfect mirror for optical frequencies. The radiation is emitted in a small cone with the maximum at an angle $\theta \approx 1/\gamma$ with respect to the reflecting angle of the incident particle (the direction of the "image" charge), with almost symmetrical intensity distribution around this axis. The radiation directivity allows to measure the beam divergence through the variation of the radiation angular distribution, and also allows direct measurement of the beam emittance, provided the beam is driven to a waist at the target.

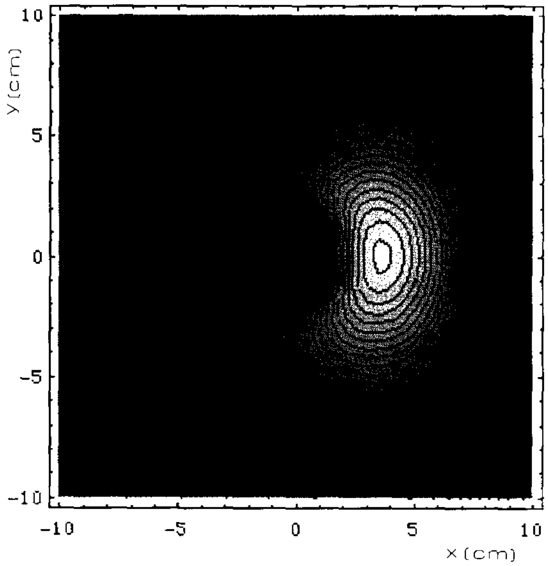

Fig. 1. OTR radiation pattern backward emitted from an aluminum target by a 1 MeV electron.

For a 1 MeV electron ($\gamma = 3$) the radiation pattern instead covers a wide angular range and is highly asymmetric. In this case the dielectric constant of the reflecting target plays a significant role in determining the radiation angular distribution, so that the simplification of an ideal mirror is no more valid.

The computed backward radiation pattern emitted by a 1 MeV electron from an aluminum target tilted at 45° around the vertical axis is shown in Fig. 1. The figure shows the radiation intensity on a 20 cm side square screen

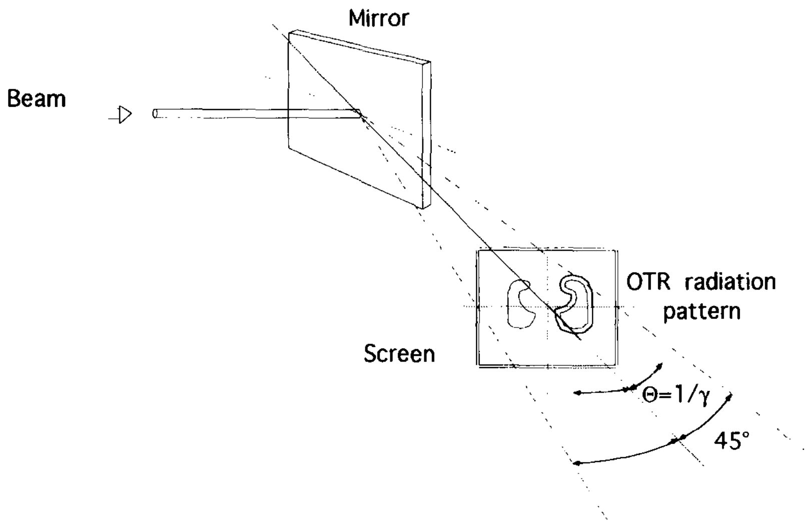

Fig. 2. Geometry used for the numerical calculations of OTR pattern.

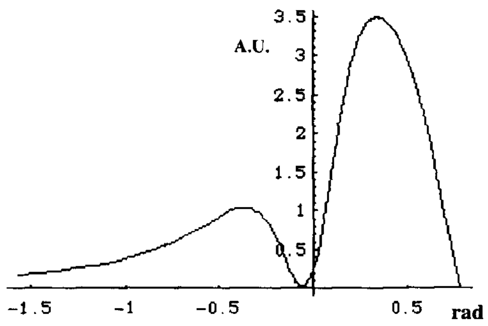

Fig. 3. Intensity distribution on the horizontal plane of OTR from an Al mirror.

positioned 10 cm from the aluminum target and centered around the direction of specular reflection of the electron velocity, i.e. the borders of the figure correspond to radiation emitted at $\pm 45°$ with respect to the beam reflection angle (see Fig. 2). In the calculation we have used a complex aluminum dielectric constant $\varepsilon = (42 + 12I)$, a tabulated value at 550 nm radiation wavelength. In this figure, as well in all successive contour plots, contours of equal intensity are plotted at constant intervals of intensity.

The asymmetry in the intensity distribution is clearly visible. It arises from the "large angle" contribution of the forward emitted radiation, that is significantly present only for directions close to the metallic surface. In fact the intensity cut-off for positive values of the abscissa is due to the finite value of the dielectric constant of aluminum, or, in an equivalent formalism, to the angular dependence of the Fresnel reflection coefficient. For an ideal metallic mirror the intensity would remain almost constant up to the direction along the surface. All these features can be seen more clearly in Fig. 3, in which we show the intensity distribution on the horizontal plane.

Here one sees the relative ratio between the two intensity maxima, together with a new feature that appears at low electron energy: in this plane the direction of minimum intensity does not coincide with the specular reflection of the electron line of flight. The difference depends on the electron energy and tends to zero for $\gamma \gg 1$. At 1 MeV the angle of minimum intensity corresponds to about -55 mrad, and around this value its energy dependence is quite accurately described by $\theta_0 = -0.5/\gamma^2$ rad.

The pattern of Fig. 1 is the result of the sum of two distinct polarization states: the first in the so called "radiation plane", i.e. the plane defined by the photon direction and the normal to the reflecting surface, and the second normal to this plane. Although for $\gamma \gg 1$ the radiation plane is in fact always horizontal, so that the two polarization states can be considered respectively horizontal and vertical, this is no longer true for low energy, at least for large angles. In this case the experimental filtering effect of a real polarimeter somewhat mixes the two polarization states. Fig. 4 and 5 show the computed intensity distributions filtered by a horizontal and vertical polarimeter respectively.

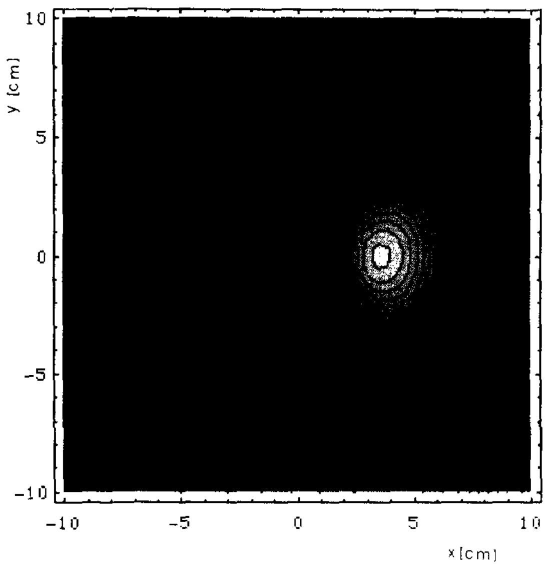

Fig. 4. Intensity distributions filtered by a horizontal polarimeter.

The strong asymmetry in the intensity distribution also reflects in a large difference between the relative intensity of the two polarization states, as can be seen in Fig. 6 in which the intensity distributions along the horizontal and vertical axes corrisponding to the maxima of the two polarization states are plotted.

3. Diagnostics use of 1 MeV OTR

The large emission angle of OTR by 1 MeV electrons poses severe conditions on the optics required to focalize

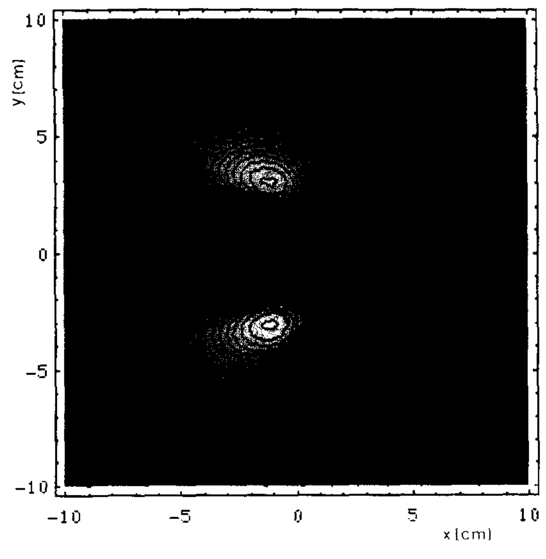

Fig. 5. Intensity distributions filtered by a vertical polarimeter.

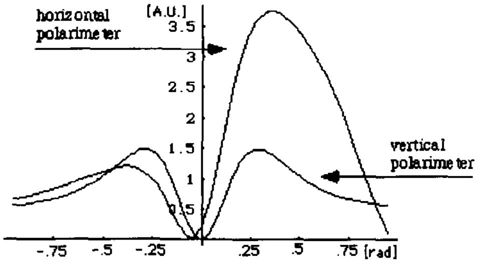

Fig. 6. Intensity distributions along the horizontal and vertical axes corresponding to the maxima of the two polarization states.

the whole radiation on a TV camera. A large diameter lens with short focal length is needed just outside the vacuum window, requiring a complex aberration free optical system in order not to introduce strong spherical aberrations.

However, the detection of the whole radiation distribution is necessary only to analyze the beam divergence, but at this energy the wide angular range covered by the radiation makes such a measurement ineffective: convolving the single particle distribution of Fig. 1 or 3 with a realistic value of beam angular spread (up to 10 mrad), no measurable variation is obtained. OTR may anyway be used to measure the transverse beam profile, with the advantages over fluorescent targets of linearity, absence of saturation and no granularity, provided sufficient intensity is available. In this case a simpler optical system can be used, because the radiation emitted around the relative maximum in the horizontal plane is sufficient for imaging the beam spot, and covers a relatively small angular spread.

A more interesting use of OTR is to monitor energy stability along the macropulse. For $\gamma \gg 1$ it is possible to demonstrate that OTR intensity integrated in a cone around the minimum emission direction, and with an aperture much less than $1/\gamma$, shows a fourth power energy dependence. The measurement of a possible variation of energy with time can be easily performed selecting the radiation with an iris and collecting it on the cathode of a photomultiplier.

At an electron energy of 1 MeV it is impossible to prove such a power dependence analytically; we have therefore integrated the single particle intensity distribution numerically in a cone of variable aperture, for different energy values around 1 MeV.

We have chosen the direction of minimum emission at 1 MeV, the beam mean energy, as cone axis, so that we can experimentally identify it. For a first estimate of misalignment error effects, we also calculated the intensity inside two cones whose axes were horizontally shifted by ± 20 mrad.

For each value of cone aperture and axis direction the energy dependence is fitted by a two free parameters power law of the type $(a\gamma^n)$.

For cone apertures up to 200 mrad the fit is rather crude, indicating that a more complex energy dependence is present, while above this value the fit is quite good confirming the validity of the analysis.

The results are summarized in Fig. 7, showing the exponent n obtained from the fit as a function of the cone aperture for the three different directions of the axis.

For small cone apertures the exponent n is not only the result of a relatively bad fit, but is also very sensitive to the cone axis direction, evidencing the influence of the

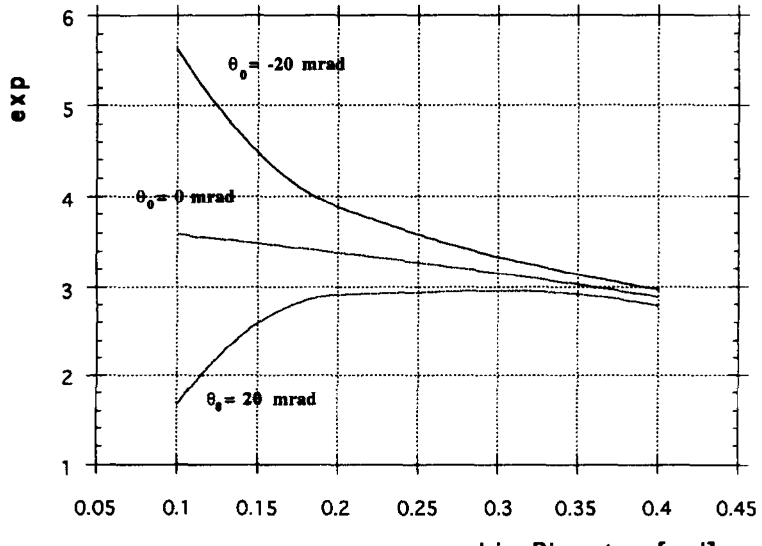

Fig. 7. Behavior of the power law exponent as function of the iris diameter for three different radiation axis directions (see text).

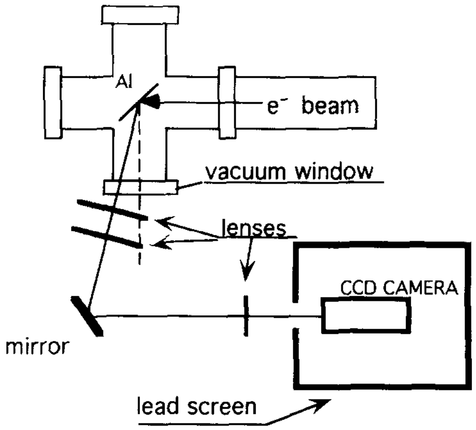

Fig. 8. Schematic layout of the experimental set-up.

dependence of the minimum intensity direction on energy. For larger cone apertures, n varies little with aperture angle, and is quite insensitive to the axis direction.

Although the exponent is somewhat smaller than in the high energy case, with an iris aperture of 400 mrad the sensitivity of intensity to energy is enough to assure an accurate measurement. We have in this case

$$\frac{\mathrm{d}I}{I} = 2.9\frac{\mathrm{d}E}{E}.$$

Integrating the output of a photomultiplier with a time constant of some tens of microseconds, we expect to be able to monitor the energy stability along the few milliseconds duration macropulse with a sensitivity of less than 1%.

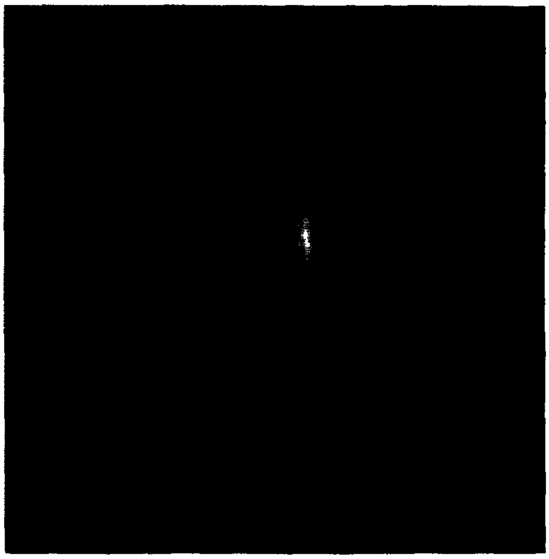

Fig. 10. OTR image filtered by a horizontal polarimeter.

4. Preliminary experimental results

The aim of the work has been to identify OTR and verify the possibility of measuring the beam transverse

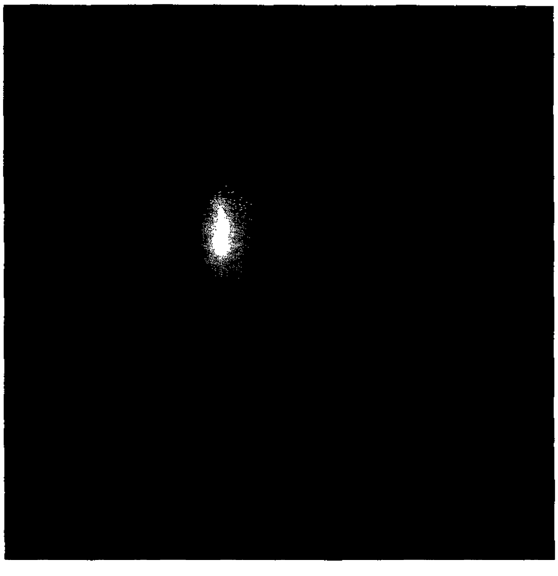

Fig. 9. Image of the OTR beam spot with 1 mA mean current and 2 ms pulse length. The full-width dimension of the spot on the target is 4 mm in the vertical direction and 2.2 mm in the horizontal one.

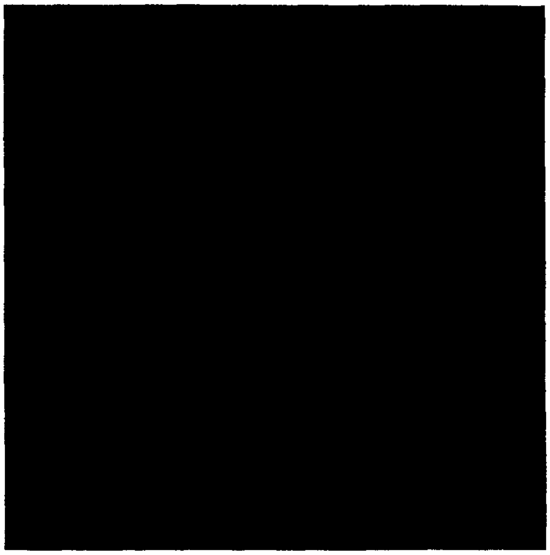

Fig. 11. Same beam condition of previous figure. The radiation is filtered by a vertical polarimeter. No significant signal can be seen over the background noise.

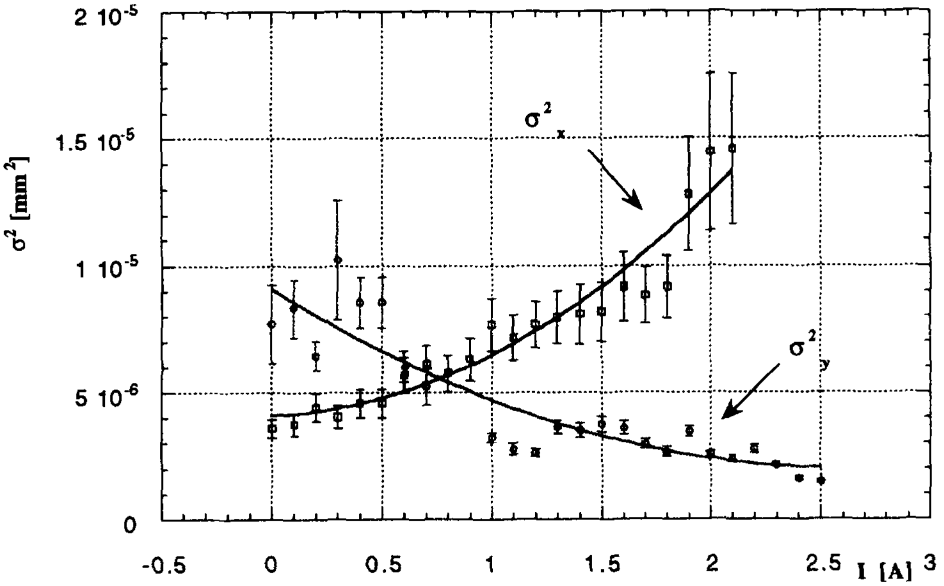

Fig. 12. Square of the beam spot size vs. quadrupole current in the horizontal and vertical planes.

profile. A polished bulk aluminum target is inserted at 45° along the injector section of the LISA superconducting accelerator, just after the 180° bending arc (a detailed description of the LISA injector system can be found in Ref. [10]).

The experimental set up is shown in Fig. 8. A three-lens telescope forms an image of the target on the optical sensor of a CCD camera. The telescope axis is at 300 mrad to the normal to the beam on the horizontal plane: the direction of the relative maximum of OTR. A mirror deflects the light to allow complete lead screening of the TV camera from higher energy radiation from the accelerator and from the target itself. The camera is a standard one, the same used all along the linac to record fluorescent target images.

In the commissioning phase of the injector, OTR was easily observed, even at a mean current that was almost an order of magnitude less than the nominal one, but quantitative measurements have been possible only when a larger current was reached. In Fig. 9 we show an OTR image obtained with 1 mA average current and a 2 ms duration macropulse. When this and the following images were taken, the transport efficiency along the arc was of about 70%, and the noise background on the pictures is due to stray electrons hitting the aluminum vacuum chamber giving rise to fluorescent radiation reflected by the mirror on the TV camera.

The nature of the observed radiation was confirmed by the insertion along the optical path of two polarimeters with respectively horizontal and vertical polarization axis. As can be seen in Figs. 10 and 11, the detected radiation results almost completely polarized in the horizontal plane, in agreement with theoretical expectations (see Figs. 4 and 5).

We have measured the variation of beam dimensions as function of the strength of an upstream, vertically focalizing, quadrupole. The results are shown in Fig. 12. From a least squares fit of the theoretical behavior, shown as a continuos line in the figure, we obtain a value of the beam transverse emittance (defined as $\varepsilon = \sigma\sigma'$) of 2.4×10^{-7} m rad in the horizontal plane and of 1.7×10^{-7} m rad in the vertical one. Very similar numbers have been obtained with different measurement sets. These values are about a factor of 2 lower than that measured before the bending arc, and this fact can be explained by the 70% transport efficiency, the arc acting as an emittance filter.

5. Conclusions

Even at an energy as low as 1 MeV, OTR shows its effectiveness as a diagnostic tool for long pulse electron beams delivered by superconducting linacs. It is free from saturation effects and surface granularities of fluorescent targets, and we have demonstrated its possible use for emittance measurements with the fixed target-variable gradient method.

Our analysis shows that the property of almost instantaneous emission of OTR can be exploited to monitor energy variation along the macropulse, with a rather high sensitivity. An experimental program to demonstrate this possibility is on schedule in the immediate future on the SC linac LISA.

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