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# BEAM DIAGNOSTICS USING TRANSITION RADIATION PRODUCED BY THE LISA ELECTRON BEAM

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**Abstract**

Optical transition radiation (OTR) measurements have been performed on the LInac Superconductive Accelerator LISA beam at the Frascati National Laboratory in 1996. The profile and the energy of a macropulse were measured for an electron beam of 12 MeV nominal energy. Results and data analysis are presented.

## 1 Introduction

The Optical Transition Radiation, OTR, is routinely used for high energy beams diagnostics. [1][2][3][4].
Transition radiation, TR, was first predicted by Frank and Ginzburg in 1945 [5][6]. TR is produced whenever a charged particle crosses the boundary between two media with different dielectric constants.
The transition radiation in the optical band is called optical transition radiation. OTR is obtained putting a thin metallic foil along the trajectory of charged particles. The characteristics of a particle beam can be analysed using the TR emitted by the beam crossing a thin metallic target. The transverse position of the emitting particles can be observed in the object plane of an optical system. The angular distribution of OTR brings also informations on the energy and divergence of the emitting particles.

The advantages of this optical technique over the classical phosphor film or chromium aluminium doped stopping flags are multiple. The TR intensity does not depend on the target thickness, the OTR targets are much thinner than the other ones so beam scattering and X-ray production are reduced. This makes OTR an almost non destructive technique.
Being OTR a phenomenon in the sub-picosecond scale, time resolved measurements can be performed, like micropulse length or beam parameters variations along a macropulse measurement's.
The TR intensity spectrum for a vacuum-perfect conductor transition is flat. For diagnostic purpose the visible frequencies of TR can be revealed using a standard CCD. The number of emitted photons per electron is of the order of the fine-structure constant over the visible spectrum, so to exploit the advantage of OTR, a very sensitive device is needed, or a high intensity beam.
In the next section it will be described how OTR can be used as a diagnostic tool and its typical experimental set-up. Some experimental results and data analysis obtained on the electron beam of the LInear Superconductive Accelerator (LISA) at the LNF will be presented[7].

## 2 Diagnostic with OTR

The conceptual design of an OTR system consists in a thin metallic target positioned at $45°$ with respect to the beam direction and an optical system which conveys the emitted radiation on a CCD camera to monitor the radiation pattern, see figure 1.

The backward emitted OTR is centred on the specular reflection direction, i.e. normal with respect to the beam direction and it has an angular aperture proportional to $1/\gamma$.

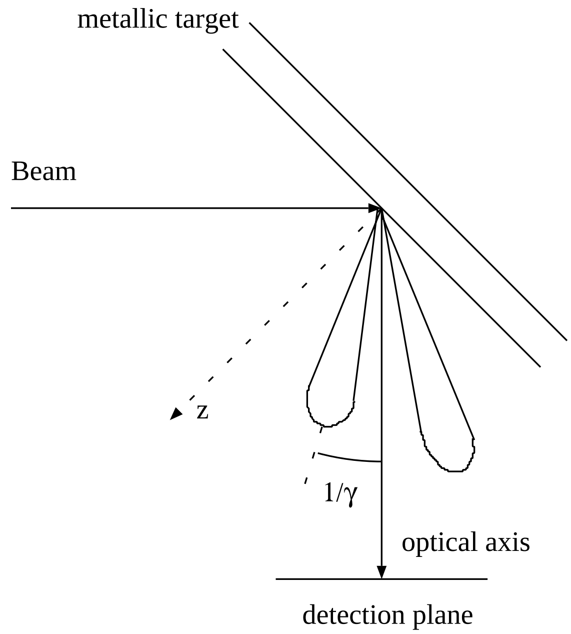


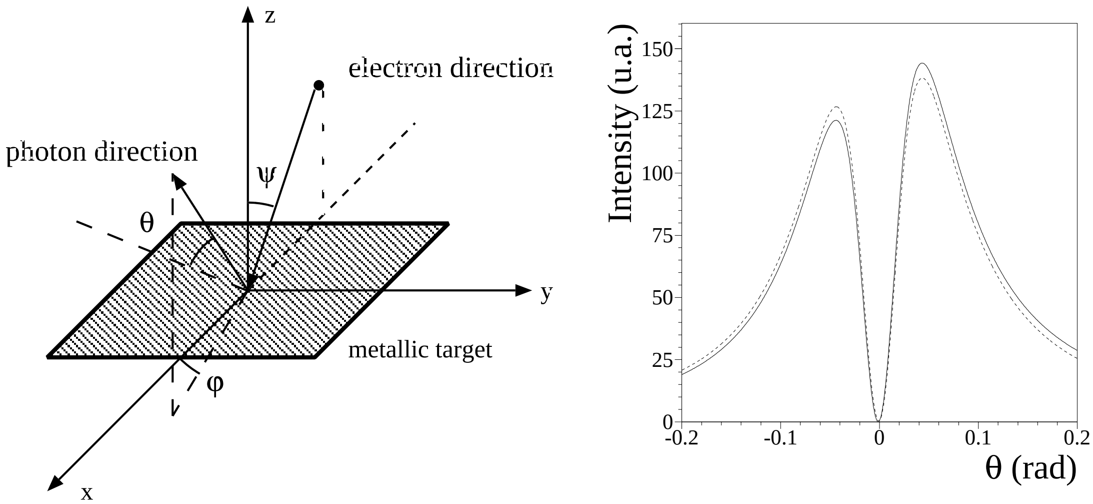

Figure 1: OTR radiation pattern

The intensity of the backward-emitted TR in a frequency interval $d\omega$ and in a solid angle $d\Omega$ in the case of a single interface crossed by an electron at $45°$ incidence (vacuum-to-perfect conductor case) is given by the following equations [8]

$$\frac{d^2 I_{||}}{d\Omega d\omega} = \frac{e^2}{2\pi^2 c}\beta^2 \frac{\left(sin\theta - \beta/\sqrt{2}cos\varphi\right)^2}{|(1-\beta/\sqrt{2}sin\theta cos\varphi)^2 - \beta^2/2cos\varphi^2|^2} \tag{1}$$

$$\frac{d^2 I_{\perp}}{d\Omega d\omega} = \frac{e^2}{2\pi^2 c}\beta^4 \frac{(cos\theta sin\varphi)^2}{|(1-\beta/\sqrt{2}sin\theta cos\varphi)^2 - \beta^2/2cos\varphi^2|^2} \tag{2}$$

We have called $||$ the *parallel plane* and $\perp$ the *perpendicular plane* to the *radiation plane*, defined by the normal to the reflecting plane $\vec{n}$ and the wave vector $\vec{k}$. The *observation angle* $\theta$ is the angle between $\vec{k}$ and the observatory. The *azimuth of observation* $\varphi$ is the angle between the x axis and the $\vec{k}$ projection on the separation plane (see figure 2a).
As it can be seen in figure 1, the radiation is emitted in an empty cone centred on the specular direction of the beam. The cone is slightly asymmetrical due to the oblique incidence on the target. A section of the cone reveals the OTR pattern with two asymmetrical lobes. The asymmetry between the lobes is maximal for $\varphi = 0$ and their distance is $\theta = 2/\gamma$, where $\theta$ is now the angle of emitted rays with respect to the direction of specular reflection of the electrons. The two lobes get more peaked as the beam energy increases. The figure




(a) (b)

Figure 2: (a) reference system; (b) section at $\varphi = 0$ and $\varphi = 60°$ (dashed) of otr angular distribution for $\gamma = 23$ and $45°$ incidence.

2b shows the theoretically calculated curve for $\gamma = 23$, expected value for LISA machine (see below) the two peaks distance is $\theta \approx 2/\gamma \approx 2/23 \approx 0.087rad$. To collect enough radiation an optical system with high angular acceptance is then required. The TR intensity is dependent on the dielectric constant $\epsilon$, but in the vacuum-perfect conductor transition it is $|\epsilon| = \infty$ for every $\omega$, that means in this case the resulting frequency spectrum is flat.
For impact angles nearby $45°$ the OTR curve is just shifted in $\theta$ of the same angle. So, the expected OTR angular distribution resulting from the folding of eqs. (1) and (2) with the divergence distribution shows a non zero intensity in $\theta = 0$ and the two peaks do not vary their height but they slightly enlarge. The strength of the effect depends on the energy and on the divergence of the beam. For values of $\gamma = 23$, the angular distribution of OTR is relatively insensitive to divergence angles smaller than $1mrad$. In this case the OTR angular distribution resulting from the whole beam does not differ substantially from the theoretical OTR curve of a single electron.

## 3 Experimental arrangement

The OTR diagnostic tool has been used on the Frascati Accelerator LISA.
An accurate description of LISA is given in ref. [9]. Figure 3 shows a schematic view of

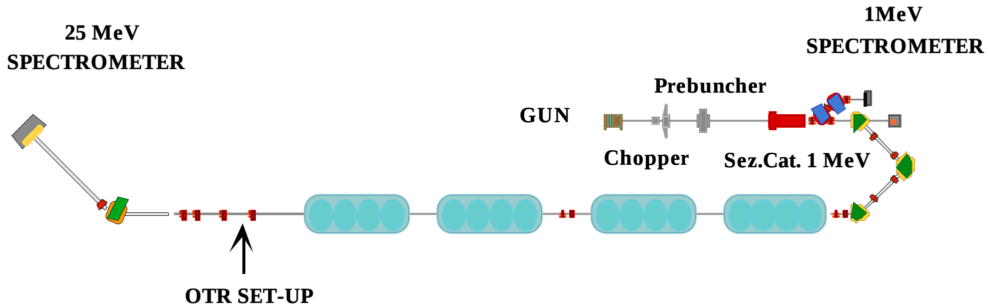


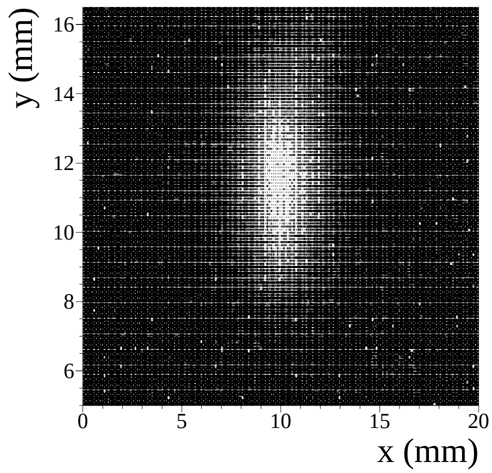

Figure 3: Schematic view of LISA linac with the position of the OTR diagnostic system.

LISA and the position of the OTR experimental set-up.

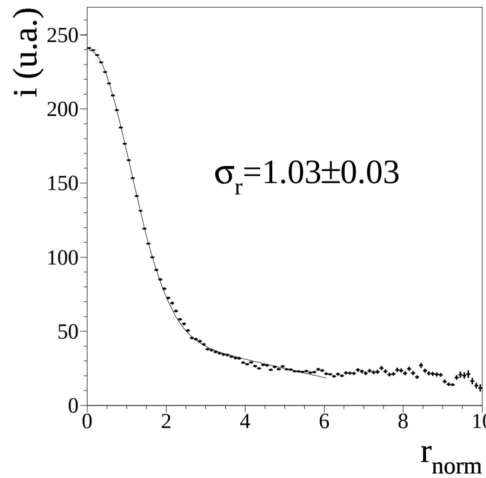
The main LISA electron beam parameters during our measurements are listed in the following table.

| | |
|---|---|
| beam energy | $12MeV$ |
| normalized emittance | $< \pi 10^{-5} mrad$ |
| dispersion energy | $2 \cdot 10^{-3}$ |
| macropulse length | $> 1ms$ |
| micropulse repetition rate | $20ns$ |
| average current | $1 \div 2mA$ |

The OTR diagnostic device was set after the first quadrupole following the superconducting cavities. The beam has at that point a nominal energy of $12MeV$.
The CCD recording the beam profile of a single macropulse was remotely controlled. The OTR emitting screen was a Kapton foil $25\mu m$ thick, coated with a $400\AA$ aluminium film. The emitted radiation coming from the accelerator vacuum pipe through a glass window is collected by the optical system situated just after the window and conveyed to a CCD. The distance between the target and the optical system is about $18cm$. The optical system has an active diameter of $6.3cm$ and a focal length of $3.6cm$. The camera has a CCD sensor made of $542 \times 582$ pixels with dimension $12.8 \times 8.4\mu m^2$,and with a total area of $6.9 \times 4.9mm^2$. The data are recorded in $256 \times 384$ matrices. The spatial calibration was based on known fiducials in the object plane.
The $45°$ angle of the TR target, the center and the axis of the optical receiving system has been positioned with a great care. A reference probe laser beam has been used in the alignement procedure.




(a)




(b)

Figure 4: (a) Typical image of the transverse beam profile; (b) Intensity plot averaged over 50 intervals versus the normalized coordinate r.

## 4 Measurements and Results

The OTR images have been recorded for different beam parameters values. The results that follow have been obtained for $1mA$ of average current and $0.5ms$ of macropulse length.

### 4.1 Beam Cross-section

An accurate analysis of the beam transverse profile has been done. With the OTR technique, the transverse distribution of the beam has been measured with a relative precision around $2\%$. Figure 4a shows a typical beam profile. A projection of the 3-D Gaussian curve was done on the x and y axis. The resulting widths evaluated by a Gaussian fit are respectly $\sigma_x = (1.80 \pm 0.03)mm$ and $\sigma_y = (2.76 \pm 0.07)mm$.
The regularity of the beam has been checked by using the variable r defined by $r = \sqrt{[(x - x_0)/\sigma_x]^2 + [(y - y_0)/\sigma_y]^2}$. It has been found a $\sigma_r = 1.03 \pm 0.03$ without correlations, as shown in figure 4b.
The Gaussian beam was divided in thin 'slices' of $0.5mm$ width. For every 'slice' a projection on the x axis and a fit was done. All the standard deviations found for each y coordinate have been plotted. The plot in figure 5 shows the substantial beam homogeneity.

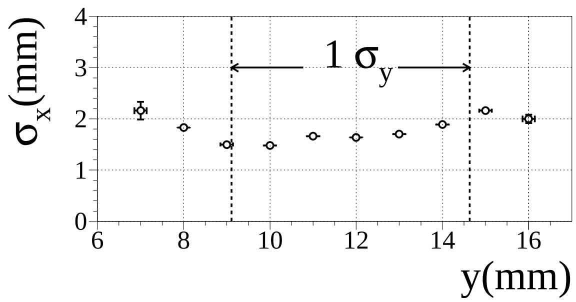



Figure 5: standard deviations of every beam 'slice' versus their baricenter coordinate y.

### 4.2 OTR Angular Distribution

The OTR angular distribution can be measured positioning the CCD sensor in the focal plane of the optical system. An example of the pattern is shown in fig. 6a, obtained subtracting the background from the original image. The expected circular shape with a large diameter due to the low energy electron beam is clearly visible. In fact, its transverse profile (fig. 6b) has the two characteristic intensity peaks at an angle $\theta = \gamma^{-1}$. This offers the possibility to evaluate the beam energy.

The divergence of the LISA beam is so small as the single electron OTR angular distribution is not changed, as results from figure 6b where the intensity I($\theta$) near $\theta = 0$ is practically zero. The LISA beam has a nominal emittance of $4\pi 10^{-7} mrad$, so being the standard deviation $\sigma$ of the order of millimeters, we expect a divergence $\sigma'$ of the order of $0.4 mrad$. In this case the OTR curve can give a good energy evaluation and no informations on beam divergence.

Deviations from the expected OTR angular distribution can be observed for large angles, where the collection efficiency of the optical system decreases.

Different sections of the OTR angular distribution have been studied, at the angles $\varphi = 0°, 45°, 60°$. The values obtained for $\gamma$ are consistent and give an average value of $\gamma = 22.3 \pm 0.01$. It has also been noted the dependence of the asymmetry of the two peaks with the angle $\varphi$.

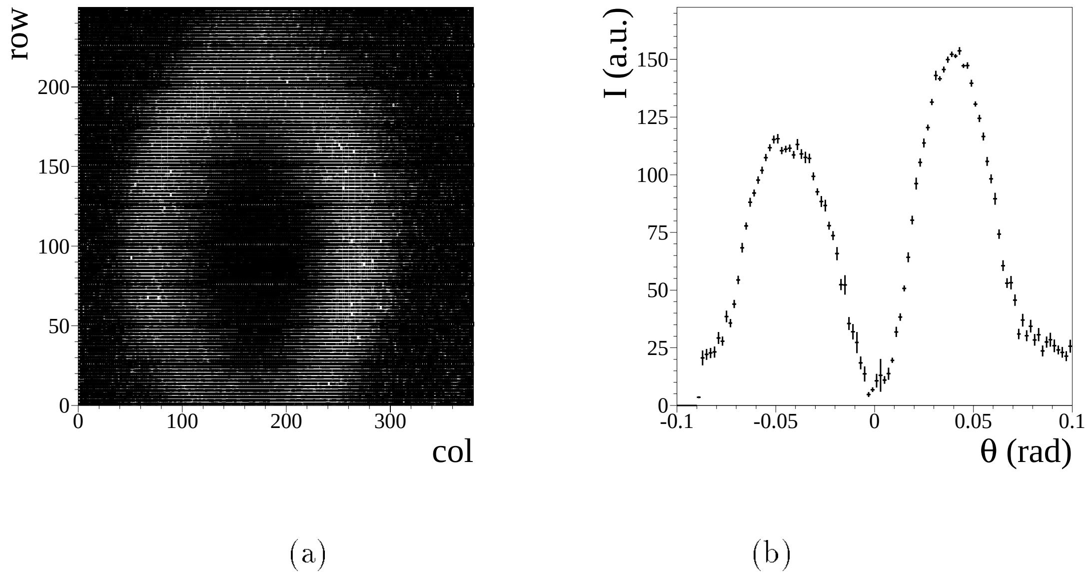



Figure 6: (a) OTR images registered in the focal plane; (b) section of previous image at $\varphi = 0$.

## 5 Conclusions

The analysis of the transverse beam profile using OTR is of excellent quality, as it permits the observation of otherwise non visible details. In particular all the parameters of the two-dimensional Gaussian distribution of the beam profile have been measured.
It has been demonstrated the possibility to evaluate the beam energy even at such low energies.


## 6 Acknowledgements

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