DETECTION OF OPTICAL TRANSITION RADIATION AND ITS APPLICATION TO BEAM DIAGNOSTICS

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Summary

Optical transition radiation produced by 40-60 MeV electrons crossing thin metallic foils has been studied in order to provide a beam diagnostic device. The radiation yield is roughly one photon per 100 electrons and the intensity appears to be Z independent ; the influence of bremsstrahlung is then fairly weak. Measurements of angular and γ dependence, spectral density and polarisation have been carried out and results are in good agreement with theories. When multiple scattering angles are negligible ($< \gamma^{-1}$), a strong energy dependence, close to γ^3 , of the light intensity radiated into small solid angles is found. Moreover, the radiation is peaked in a direction making an angle γ^{-1} with the beam axis. Suitable optical arrangement make it possible beam position and profile determination. Measurement of the polarisation plane rotation by means of a scanning mirror provides a method of determining the incident angle of the beam onto the target. This device looks promising for diagnostics on particle beams-electrons as well as protons- with normalized energies γ in the range $1-10^3$.

I. Introduction

It is well known that transition radiation (T.R) is emitted whenever a charged particle moving uniformely along a straight line crosses the interface of two media with different dielectric constants. Theoretically predicted in 1946 by Ginzburg and Frank[1], this radiation has recently given rise to renewed interest because it might permit to measure ultra relativistic particle energies or to detect and identify particles of known energy.

The simplicity of the measurement based upon T.R, as compared with the complexity of the other methods available at very high energies (Cerenkov counters, scientillators) has been pointed out by many authors.

Since Garibyan established in a straightforward and classical way, the theory of T.R in the relativistic case[2], experiments have been performed both in the optical and in the X-ray region of the spectrum.

For electrons or positrons with normalized energy γ lying in the range $1 - 10^3$, the radiation in the optical region (i e from 2500 to 6000 Å) can be investigated, especially when the flux of incident particles is not too low (the yield of photons created in this bandwidth , in a single metal-vacuum transition is typically of the order of 10^{-2} photon per incident electron).

Prunster et al[3] using a stack of metallic foils have shown the logarithmic energy dependence of the over all optical T.R in agreement with Garibyan's theory.

In other respects, Alikanyan et al[4], have demonstrated that the fractional part of the optical T.R emitted in a cone with apex angle $\Theta \ll \gamma^{-1}$ is proportional to γ^4 . Experimentally, they obtained an energy dependence close to γ^3 . The same dependence was also found by the authors[5].

In the above cited experiments the emitted light was deflected by one or many mirrors (in the case of a stack of foils) crossed by the beam and the influence of such mirrors was not clearly precised; some discrepancies thus appeared in the results as compared with those obtained in other experiments or predictions[6-9]

In the present work, the goal of the authors was to assert the main properties of the T.R and to provide a beam diagnostic device using this radiation as a tool.

II. Theoretical background

The intensity of the forward-emitted T.R in a frequency interval $d\omega$ and in a solid angle $d\Omega$ is expressed by the following formula, derived by Garibyan in the case of a single interface crossed at normal incidence (medium-to-vacuum case) :

$$\frac{d W}{d\omega d\Omega} = \frac{e^2\beta^2\sin^2\theta.\cos^2\theta}{\pi^2 c(1-\beta^2\cos^2\theta)^2} \cdot \left| \frac{(\varepsilon-1)(1-\beta^2-\beta\sqrt{\varepsilon-\sin^2\theta})}{(\varepsilon\cos\theta+\sqrt{\varepsilon-\sin^2\theta})(1-\beta\sqrt{\varepsilon-\sin^2\theta})} \right|^2 \quad (1)$$

where ε is the complex dielectrique constant of the medium and θ the angle of emission with respect to the direction of the electron velocity.

The backward radiation (vacuum-to-medium case) is easily obtained by changing in this formula β in $-\beta$.

The problem of the radiation produced when the particle crosses the interface at oblique incidence was considered in a number of papers[10-12]. (For an exhaustive bibliography on T.R see also 13 and 14).

In the general case, the obtained formulae are rather cumbersome. However, a noticeable simplification may be obtained in considering the model of a perfectly conducting metallic foil. In this case, T.R simply reduces to the radiation produced in an annihilating or creating pair process involving the incident electron and a virtual image positron :

$$\frac{d^2W}{d\omega d\Omega} = \frac{1}{4\pi^2 c} \left| \frac{-e\sin\theta}{1-\beta\cos\theta} + \frac{e\sin\theta'}{1-\beta\cos\theta'} \right|^2 \quad (2)$$

where θ' is now the angle of emission with respect to the direction of the positron velocity.

In the medium-to-vacuum case and for relativistic particles ($\beta \to 1$) the second term in equation (2) may be ignored provided that the incidence angle of the particle is not too close to $\pi/2$ (non grazing incidence) . The T.R is then peaked in the direction of the electron velocity.

The situation is reversed in the vacuum-to-medium case. These different cases are summarized in figure 1.

Because of this dipole-type emission, T.R is longitudinally polarized, the electric vector lying in the plane of the particle velocity (or its image) and the direction of observation.

Formula (2) reduces to formula (1) in the assumptions $|\varepsilon|>>1$, $\beta \to 1$, $\theta << 1$ and it can easily be shown that the emission maximum occurs at an angle $\theta_m (\text{or} \theta'_m) \simeq \gamma^{-1}$.

Another characteristic feature of T.R is that the spectral density is practically frequency independent in the optical region for most of the metals (an exception being silver in the transparency region, around $\lambda \simeq 3400$ Å).

The integration of (2) over θ or θ' in the angular interval $(0 - \theta)$ yields to the following results :

$$\text{For } \theta << \gamma^{-1} : \frac{dW}{d\omega} \simeq \frac{e^2}{2\pi c} (\gamma\theta)^4 \quad (3)$$

$$\text{while for } \theta >> \gamma^{-1} : \frac{dW}{d\omega} \simeq \frac{e^2}{\pi c} \{L_n (\gamma\theta)^2 - 1\} \quad (4)$$

It therefore follows that the fractional part of T.R emitted into small solid angles increases with energy as γ^4 while the total intensity is a logarithmic function of γ.

Dividing equation (4) by $\hbar\omega$ and integrating over ω in the frequency interval (ω_1, ω_2) gives the total number of T.R photons:

$$N = \frac{\alpha}{\pi} \{L_n (\gamma\theta)^2 - 1\} \cdot L_n \frac{\omega_2}{\omega_1} \quad (5)$$

where $\alpha = \frac{e^2}{\hbar c}$ is the fine structure constant.

The order of magnitude of the T.R yield in the optical region (i e from 2500 Å to 6000 Å) is thus of one photon per 100 incident electrons.

In order to increase the T.R yield a stack of foils must be used. In the case of two foils arranged in such a manner that the front face of the second one plays the role of a mirror for the radiation produced on the back side of the first one, we have :

$$\frac{dW}{d\omega d\Omega} = \frac{1}{\pi^2 c} \frac{e^2 \sin^2\theta}{(1 - \beta\cos\theta)^2} \sin^2\left[\frac{\pi L}{\lambda} (\gamma^{-2} + \theta^2)\right] \quad (6)$$

where L is the length of the electron path between the two foils, λ the wavelength. The second factor in equation(6) takes into account the interference effects between the two sources of radiation.

III. Experimental arrangement

Experiments were performed using either a single thin foil inclined 45° on the beam direction or a two-foil arrangement in which the second foil reflected the light produced at the back of the first foil into the same direction as its own radiation (fig.1).

Samples were prepared by vacuum deposition of aluminium, gold or silver on mylar foils 6 µm or 3 µm thick. 100 µm thick quartz foils coated with a thin layer of evaporated aluminium were also used. Metal thicknesses were about 0.3 µm. These samples were placed directly in a special chamber at the end of the last accelerating section of the Saclay 60 MeV electron linac.(fig.2).

Although in most of these experiments the multiple scattering effect was fairly weak, the samples were incorporated in a mechanical arrangement and a remote controled valve allowed the positioning of this device in the beam. In order to eliminate the Cerenkov radiation produced in the dielectric supports of the layers the surrounding wall of the chamber containing the samples was blackened by a graphite spray.

T.R patterns recording was performed using a mirror M_1 scanning the angular interval ± 2° around 45°. This mirror and a multiturn potentiometer were driven by a stepping motor. Light emerging from the silica window of the vacuum chamber was reflected by M_1 and passed through an iris diaphragm D_1 with radius R_1 fixed by remote control. This diaphragm was located in the focal plane of a nonbrowning, achromatic and non-reflecting lens L_1 (focal distance f_1 = 142 cm).

This optical arrangement presents the advantage of transmitting photons emitted in a cone with apex angle θ_o= arctan R_1/f_1 whatever the point-source position and takes thus into account the transverse spread of the analysed beam. Two other nonbrowning lenses L_2 and L_3 and mirrors M_2 and M_3 were used to focuse the light on a 56 AVP photomultiplier enclosed in a lead box which suppresed the background noise produced by gamma-rays.

Beam positioning and beam profile measurements were performed by means of a two-crossed slits device D_2 located in the anti-principal plane of the samples under test. These slits could be deplaced both in the horizontal and vertical plane by remote control and defined an aperture of 1 mm². Recordings were obtained by the same technique as mentioned above. In one run this device was removed and replaced successively by a TV camera with a 55850 type vidicon tube or photo-camera.

A polarizer using a disc of Polaroïd was also mounted on a rotating device and was operating while the mirror M_1 was scanning in the horizontal plane. All the optical elements were positioned along the line of sight of the linac and good optical alignement was achieved using the light emitted by the cathode of the linac. In most of the experiments this light was taken as a reference for the electron beam centering. It was also possible to use as reference a cross-shaped diaphragm placed in the planeof D2 and illuminated by a lamp mounted outside the T.R optical path.

The experimental apparatus being located across the direct electron path (instead of the deviated path as in4), it was necessary to set up a sampling technique in order to record on the X-Y plotter the contribution of electrons selected at a given instant in the current pulse and having thus a well defined energy (instead of the 40-60 MeV energy spread due to the beam-loading effect, during the 1 µs current pulse). Finally interference filters were also placed on the optical path. The general experimental set up is shown on figure 3.

IV. Results

The overall T.R photon yield in the case of a single boundary was measured relatively to the tungsten cathode light emission at 2750°C using Plank's formula for the blackbody radiation. This procedure which avoids some uncertainties on P.M bandwidth and optical transmission factor led to results in agreement with the theory.

Figure 4 shows a typical recording of the T.R pattern which has been obtained in the case of a single boundary when both the mirror M_1 and the polarizer were operating. The upper enveloppe of this curve represents the parallel component of T.R while the lower one represents the perpendicular component. (The lower trace in figure 4 represents the cathode light in absence of the electron beam). This pattern is similar to the one obtained in the case of a two foil arrangement, but the amplitude is approximatively reduced by a factor 2. In the latter case, no significant change in the envelopes arose by variation of the Z of the material (Al, Ag Au). It was then asserted that these patterns were unaffected by optical bremsstrahlung. Assumption was then made that the perpendicular component arose only from the method of measurement owing the fact that the electron beam viewed from a point in the aperture D_1 is an extended source of radiation, giving thus a partially polarized light.

Moreover, no significant coherence effect could be detected in the two foil arrangement. This was probably due to the fact that the signals were blurred out in the 150 Å bandwidth filters as well as in the unequal path lengths of electrons between the non parallel foils.

Measurement of the peak-to-peak width on the T.R pattern was carried out for different values of opening angles θ_0 and the extrapolation to vanishing angles led to a value of the normalized energy γ with a 3% precision.

It was observed that when the polarizer was kept in a fixed position, the registrated pattern exhibited, for certain values of the steering dipole currents, a strong dissymetry in the peak amplitudes. This effect was associated with the mean inclination of the electron beam with respect to the optical axis.

Figure 5 shows the effect of an inclination in the vertical plane. Considering two symmetrical positions of the scanning mirror M_1, with respect to the optical axis, it is seen that, in order to restore the same level for both peaks, it is necessary to rotate the polarizer by an angle ϕ such that :

$$\tan \beta \;.\; \tan \frac{\phi}{2} \;=\; \tan \theta$$

For a 30° measured phase shift, the calculated incidence angle in the vertical plane was $\beta \approx 2$ m.rad for the two positions corresponding to the peaks of the pattern. This method of measuring the incident angle of the beam onto the target gives a resolution of about 0.5 m.rad both in the horizontal and in the vertical plane.

Concerning the use of T.R light in a beam profile monitor, a spot corresponding to the actual size of the electron beam could be observed on the TV scope and was still visible at a mean current of 3.10^{-8} A. This may be compared with results obtained elsewhere in a beam profile monitor using the synchrotron radiation light[15] for 400 MeV electrons (bending magnet radius R = 57 m ; lengh of the observed track ℓ = 30 cm). Sensitivities in both cases are of the same order of magnitude.

Figure 6 shows a photography of different spots when the electron beam was displaced by means of the steering dipole currents of the last accelerating section.

Figure 7 shows as an example the intensity profile obtained at the exit of the linac with the two slit arrangement, at a fixed instant of the current pulse, in the form of isodensity curves. It can be seen that the half density line is roughly a circle with a 3 mm diameter.

V. Conclusion

The experimental results obtained in this work correspond in a satisfactory way to the theoretical predictions. An attractive feature of the proposed device for beam diagnostics is its simplicity and non-destructive character, though information about lifetimes are not yet available.

A device of this type using the T.R light is now being constructed at the LAL Orsay in the group of P. Brunet, in order to visualize the 300 MeV electron beam on the positron source target.

Other experiments are planed in order to obtain automatic and fast recording of the patterns.

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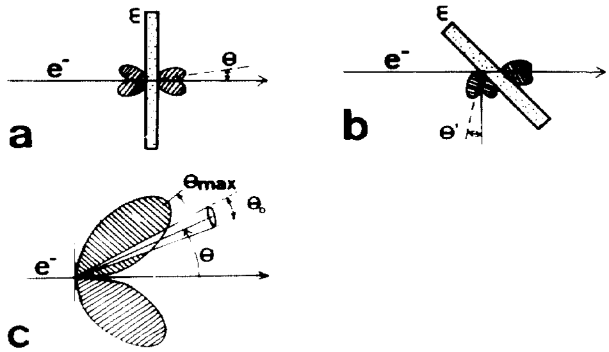

Figure 1 : Transition radiation patterns
a - normal incidence case ;
b - oblique incidence case ,
c - notation used.

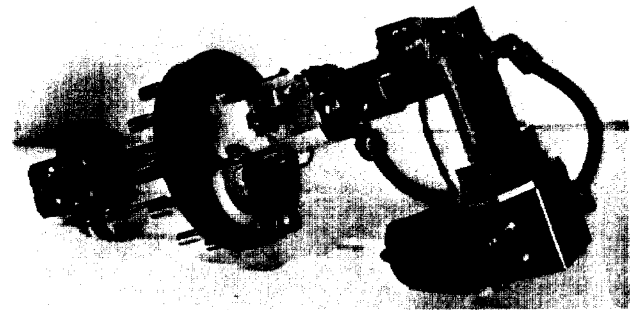

Figure 2 : Photography of the transition radiation block-monitor.

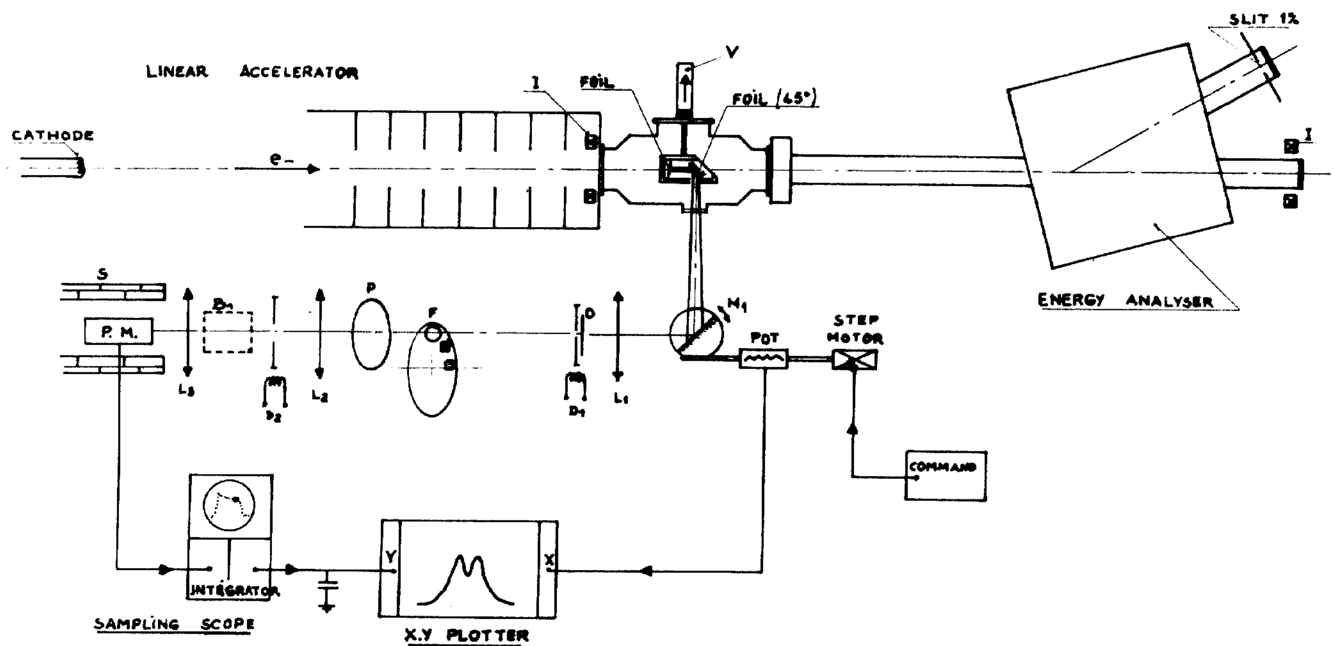

Figure 3 : General experimental arrangement
O shutter ; D_1,D_2 diaphragms ; L_1, L_2, L_3 lenses ; P polarizer ; F filters ; PM photo-multiplier ; B_1 vidicon or photo-camera ;
I ferrite monitor.

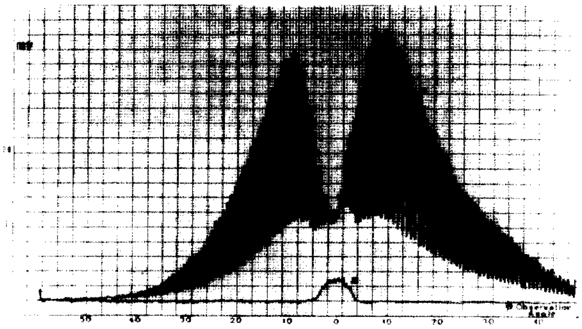

Figure 4 : T.R pattern recording .
1 - Transition Radiation
2 - cathode light
Peak current = 13 mA ; pulse width = 1 μs ; repetition rate = 62.5 Hz ; energy = 60 MeV, selected instant in the pulse = 0.8 μs ; θ_0 = 2.8 m.rad.

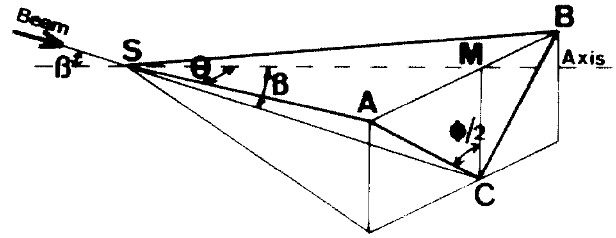

Figure 5 : Schematic diagram showing the effect of an inclination β in the vertical plane.

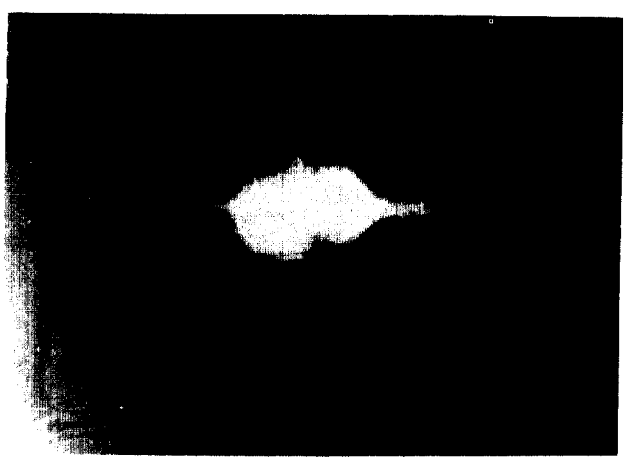

Figure 6 : Beam profile observed by means of a TV camera (two Al coated foils)
peak current = 13 mA ; pulse width = 1 μs ; repetition rate : 62.5 Hz.

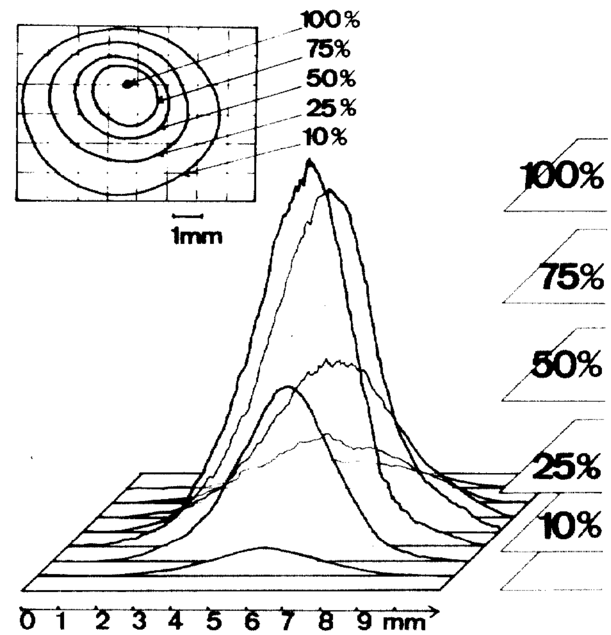

Figure 7 : Three dimensional plot of the intensity profile and isodensity curves.
Peak current : 13 mA ; pulse width : 1 μs ; repetition rate : 62.5 Hz ; selected instant in the pulse : 0.8 μs.