High Resolution Beam Monitoring with Optical Transition Radiation at 3 MeV Electron Energy

A. Specka, D. Bernard, R. Guirlet[1], F. Jacquet, P. Miné, B. Montès, R. Morano, P. Poilleux
(Laboratoire de Physique Nucléaire des Hautes Energies, IN2P3 - CNRS),
F. Amiranoff (Laboratoire d'Utilisation des Lasers Intenses),
J. Morillo (Laboratoire des Solides Irradiés, CEA/DTA/CEREM/DTM),
Ecole Polytechnique, 91128 Palaiseau, France

Abstract

In the framework of the *plasma beat wave accelerator* experiment at Ecole Polytechnique, high precision position and focussing monitoring of a 3 MeV electron beam is needed. A device is proposed that uses backward *optical transition radiation* (OTR) from a tilted metal foil held into the beam. For an electron energy of 3 MeV, OTR is emitted within a large solid angle (typical apex angle about 40°) around the direction of specular reflection. The design requirements are a ***high resolution*** of the imaging optics ($\approx$ 10 μm), a ***high sensitivity*** ($\approx$ 10 μA beam current, not focussed), robustness, and low cost. A prototype has been constructed and successfully tested. A similar device will be used for adjusting a laser focal spot on an electron focal spot, and for monitoring the beam on entry and exit of a gas vessel.

1. Introduction

The need for ever increasing particle energies at reasonable accelerator size has led to numerous investigations of new techniques to increase the accelerating electric field. One of these techniques is the plasma beat-wave acceleration (PBWA) scheme, proposed by Tajima and Dawson [1].

In the PBWA experiment at Ecole Polytechnique two high-intensity Nd-laser pulses of slightly different wavelengths (YAG, 1064 nm and YLF, 1053 nm) are focussed in a vessel containing hydrogen gas at a pressure of 2 mbar ($\approx$ 1.5 Torr) and create almost instantaneously a fully ionized plasma by multi-photo-ionization. The beating of the two light-waves provides a longitudinal electric force which oscillates with the frequency difference $\Delta\omega = \omega_2 - \omega_1$ of the two lasers. If the frequency difference is equal to the plasma frequency $\omega_p = \sqrt{e^2 n_e/\epsilon_0 m_e}$, this so-called ponderomotive force resonantly excites a longitudinal relativistic electron plasma wave (Lorentz-factor $\gamma = \omega_1/\omega_p \approx 100$), i.e. spatial and temporal variations of the electron density n_e. The charge separation produces a longitudinal electric field of up to several GV/m. A relativistic electron with the right phase can catch the wave and, riding from the crest to the trough of the wave, gain energy from the potential difference [2].

So far, at Ecole Polytechnique the first two stages of the experiment, i.e. plasma creation and beat-wave generation have been studied [3]. The injection of 3 MeV electrons from a Van-de-Graaff accelerator is scheduled for 1994.

The laser beams are focussed to form a plasma of about 100 μm (FWHM) width and about one centimeter length.

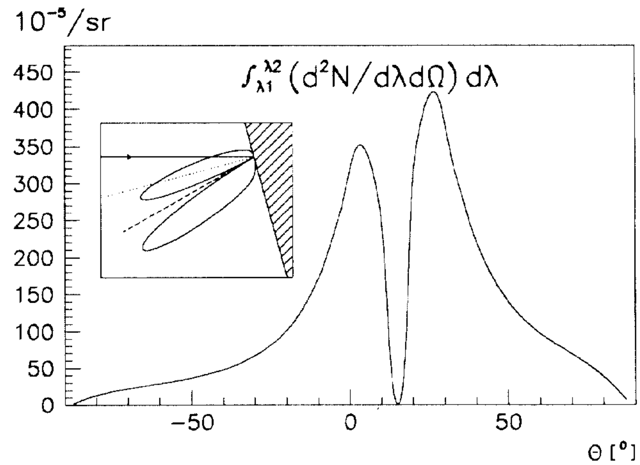

Figure 1: *Angular photon distribution and corresponding emission pattern for 3 MeV electrons*

Thus, the injected electron beam has to be focussed and positioned with high accuracy, i.e. spot position and size have to be monitored with a precision of order 10 μm.

In the past 20 years, beam spot visualization using backward optical transition radiation has proved to be a useful, simple and inexpensive method [4],[5], since conventional imaging optics and video (CCD) cameras can be used.

2. Transition radiation intensity

When a charged particle crosses the boundary between two media with different refractive indices, electromagnetic radiation is emitted. This phenomenon is called *transition radiation* (TR) [6]. The case where one of the media is the vacuum (n=1), and where the particle is relativistic ($\gamma = E/m \geq 2$) is generally considered. The spectral and angular distributions depend on whether the particles cross the boundary from medium to vacuum (forward-TR or vice versa (backward-TR).

In the case of forward-TR, the photons emitted by an appreciably relativistic particle are mainly in the X-ray domain. The number of photons per wavelength interval shows a $1/\lambda$ rise up to a cutoff frequency $\omega_c = \gamma\omega_P$ where ω_P is the plasma frequency of the medium[2]. The total number of emitted photons is then of the order of $\alpha\gamma$ where α is the fine structure constant.

On the contrary, the spectral photon density for backward-TR is proportional to the reflectivity of the medium, which drops to zero for frequencies above ω_P. It is also inversely proportional to the wavelength, and therefore emission takes place mainly in the visible and in

[1]Now at: DRFC, CEA Cadarache, France

[2]For most metals, $\hbar\omega_P$ is of the order of 10–20 eV

the near UV (*optical transition radiation*,OTR). The total number of emitted photons is of the order of α.

The angular intensity distribution is centered around a nominal axis of emission. In the case of forward TR this direction is the particle trajectory itself. In the case of backward-TR it is the direction of specular reflection of the particle on the boundary. The emission vanishes in the nominal direction and is maximal on a cone around the nominal direction with a half apex angle γ^{-1}. In the case of normal incidence, the intensity distribution is symmetric around the nominal axis. For oblique incidence the pattern is dissymmetric, becoming symmetric only in the ultra-relativistic limit. In this latter case the (double differential) angular and spectral photon density for backward-TR is given by [4]:

$$\frac{d^2N}{d\omega d\Omega} = \frac{\alpha}{4\pi^2} \cdot \frac{R(\omega)}{\omega} \cdot \frac{\beta^2 \sin^2(\theta+\psi)}{[1-\beta\cos(\theta+\psi)]^2} \qquad (1)$$

where θ is the angle of observation with respect to the normal to the boundary, $\beta = v/c$, ω is the frequency, and $R(\omega)$ is the reflectivity of the medium.

In the present application we monitor a 3 MeV electron beam ($\gamma = 6$) and the ultra-relativistic limit is not sufficiently accurate. Hence, we have used rather the exact and more complex expression given in [4]. The numerical results given here apply for backward-TR in oblique incidence at an angle of $\psi = 15^{\mathrm{O}}$ on aluminum and for a spectral domain from 400 nm to 800 nm. Figure 1 shows the number of photons per unit solid angle as a function of θ in the plane of incidence. The corresponding emission pattern is included in the figure.

The quantity of collected OTR photons depends on the angle of observation θ and the numerical aperture[3] $\Delta\theta$ of the imaging optics. Figure 2 shows the calculated dependence of the collected energy on the numerical aperture for various observation angles. Around the angles of maximum

[3]half apex angle of the aperture cone

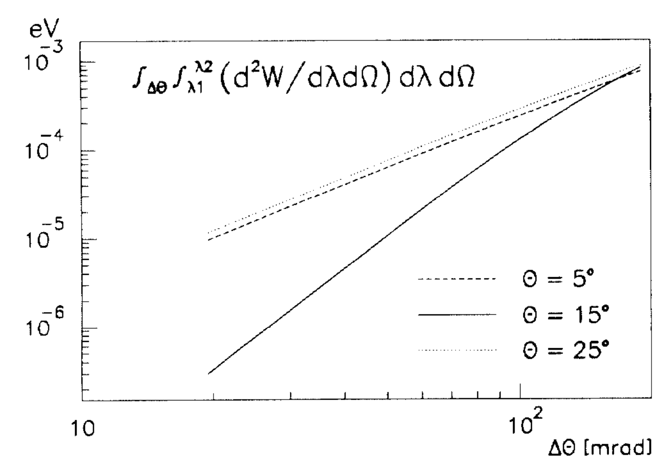

Figure 2: *Dependance of collected TR energy per incident electron on numerical aperture for different angles of observation*

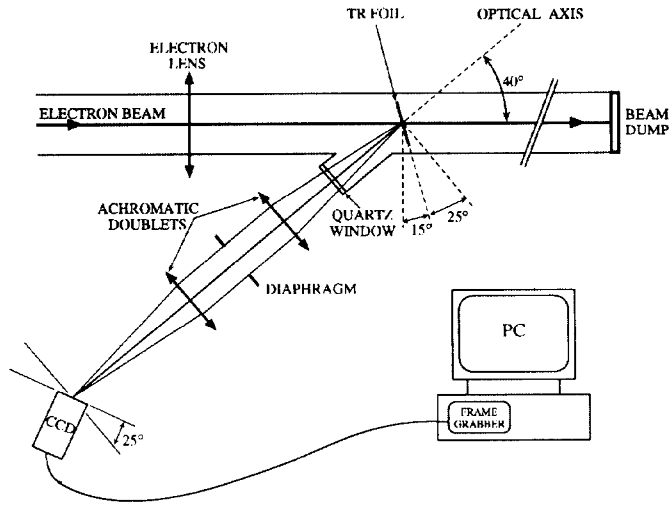

Figure 3: *Experimental setup*

emission $\theta_- = \psi - \gamma^{-1} \approx 5^{\mathrm{O}}$ and $\theta_+ = \psi + \gamma^{-1} \approx 25^{\mathrm{O}}$ the intensity grows with the square of $\Delta\theta$. Around the angle of minimal emission $\theta = \psi = 15^{\mathrm{O}}$ the intensity grows with the fourth power of $\Delta\theta$.

The radiant energy for $\Delta\theta = 100$ mrad at $\theta = \theta_+$ is $0.29 \cdot 10^{-3}$ eV per electron or 0.29 nW per μA beam current. The photon yield is $0.13 \cdot 10^{-3}$ photons per electron or $8 \cdot 10^{11}$ photons per second and μA. Taking into account the spectral OTR distribution one obtains the corresponding luminous flux of $0.17 \cdot 10^{-9}$ lumen/μA. A beam spot of 1 mm^2 size then has a luminous exitance of $0.17 \cdot 10^{-3}$ lux ($0.16 \cdot 10^{-4}$ footcandle) per μA beam current which gives sufficient light yield for high sensitivity CCD cameras for the range of currents in our application.

3. Experimental setup

Figure 3 shows the experimental setup used for the test of the prototype of the beam profile and position monitor (BPPM). A magnetic solenoid lens focusses the parallel continuous electron beam on a 1.5 μm thick aluminum foil which is tilted by 15^{O} with respect to the beam axis. Beam current ranges up to 200 μA. A fused silica window at 40^{O} with respect to the beam axis allows observation of the spot at the angle of maximal emission, i.e. $\theta = 25^{\mathrm{O}}$. A two-lens optics images the spot on the sensor of a CCD camera[4]. The video signal is read by a frame grabber card[5] inside a PC for image processing.

Besides high resolution, the design of the imaging optics was governed by two other demands: high numerical aperture and a long working distance (about 200 mm). The size of the object field fixes the magnification at unity.

A symmetric system of two achromatic doublets of 200mm focal length located on both sides of an iris diaphragm was found to satisfy these demands. The cemented achromatic doublets[6] are optimized for spherical aberration at infinite conjugates.

[4]COHU 6500
[5]EPIX 4MEG VIDEO, Aries, France
[6]Melles Griot LAO225

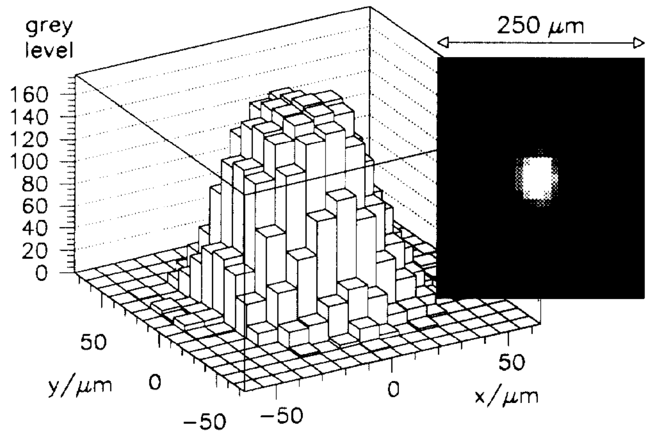

Figure 4: *Focal spot (125 μA, 1 ms)*

For unit magnification the object plane (i.e. TR foil) is at the front focus of the first lens, the image plane (CCD) at the back focus of the second lens, and the rays are parallel between the two lenses. In this case third order aberrations of odd order in image height cancel. The third order spherical aberration then dominates. For the extreme marginal ray at 90 mrad we calculate an aberration of about 50 μm at paraxial focus, giving about 8 μm standard deviation at best focus. Comparing this number to the pixel size (about 10 μm) and to the diffraction limit (diameter of the Airy-disc, about 7 μm at 500 nm), we can state that the optical system is nearly diffraction limited and that its resolution is matched to the detector.

The optical axis is at an angle of 25° with respect to the normal to the foil. In order to maintain image sharpness over the entire field, we have tilted the image plane (CCD) as well. This introduces a slight but quite tolerable image distortion of less than 1% at field edge. The precision on the tilt angle is not critical to resolution.

4. BPPM performance

The sensitivity of the BPPM is sufficiently high to visualize the parallel beam spot (about 1mm diameter) at 10 μA current at 20 ms exposure time. This is particularly useful during the beam alignment.

Figure 4 shows a typical focal spot at 125 μA and 1 ms exposure time. We found typically standard deviations of 20 μm for optimally focussed spots. As this is rather close to the estimated resolution limit of the system, actual spot sizes might even be smaller.

Before our test run, the motor turning the rubber belt of the accelerator has been magnetically shielded in order to suppress beam rotation. When operating the camera at 20 ms exposure time we have observed a residual rotation of the focal spot with an amplitude of about 0.3 mm. The movement is probably due to residual fields and still too large for the beat-wave experiment. By reducing the exposure time to 1 ms we were able to get one single image of a spot per video frame. In order to obtain a stable spot, we are thinking of pulsing the electron beam and synchronizing it with the oscillation of the residual field.

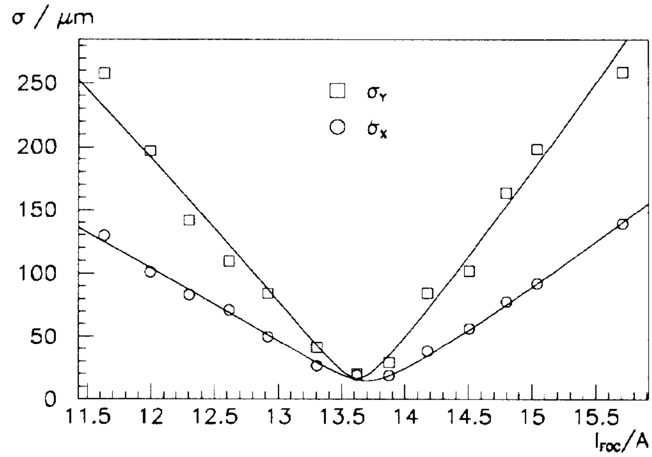

Figure 5: *Spot sizes σ_x and σ_y as a function of the current in the magnetic lens. The curves are fitted theoretical beam envelopes. (125 μA, 1 ms)*

By tracing the spot size as a function of the current in the focussing lens we can measure the beam emittance[7] (Figure 5). We obtained an upper limit for the emittance of 0.03 mm×mrad.

The γ radiation noise was tolerable and could easily be subtracted, if present. No significant radiation damage to the camera (dead pixels) or the optics was observed.

5. Conclusion and future developments

Beam profile and position monitoring with OTR at 3 MeV has been successfully tested. It meets the specifications for the beat wave experiment of high resolution, high sensitivity, robustness and low cost. Focal spot sizes of 80 μm in diameter (4σ) have been measured.

A similar device will be used at the entrance of the gas vessel, and inside the gas vessel for the alignment of the laser and electron focal spots. Viewing the laser focus and the electron focus with the same apparatus will reduce systematic errors.

6. Acknowledgements

We would like to thank R. Chehab and L. Wartski for many fruitful discussions on the subject of TR. Very efficient technical support from the Van de Graaff crew (P. Laplace et T. Perrin) and from the PNHE workshop is warmly acknowledged.

7. References

1. T. Tajima, J. M. Dawson, Phys. Lett. **43**, 267 (1979)
2. P. Mora, J. Appl. Phys. **71**(5), 2087 (1992)
3. F. Amiranoff et al., Phys. Rev. Lett. **68**, 3710 (1992)
4. J. Bosser et al., Nucl. Instr. and Meth. **A238**, 45 (1985)
5. X. K. Maruyama, R.B. Fiorito and D. W. Rule, Nucl. Instr. and Meth. **A272**, 237 (1988)
6. V. Ginzburg and I. Frank, JETP **16**, 15 (1946)

[7] We define the emittance as the product of the standard deviations of the spatial and angular intensity distributions measured at a focus. The surface of the phase space ellipse containing 95% of a Gaussian beam is $\approx 6\pi$ times higher.