Beam Diagnostics using Transition Radiation *

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Abstract

Transition radiation emitted from a thin foil in the beamline has become a preferable method for cost efficient and comfortable beam diagnostics in the regime of intercepting monitors. The optical part of the produced radiation spectrum allows the use of commercial standard CCD cameras for beamspot imaging and transverse diagnostics. A full two dimensional intensity distribution can be easily provided to the operator by use of fast graphical data processing which also allows to determine the transverse beam parameters. The OTR diagnostics at the S-DALINAC [1] is routinely used to measure the complete set of transverse beam parameters as well as to obtain the energy spread by projecting the energy distribution on a transverse axis. Furthermore bunch length measurements were made using the millimeter wavelength range of the transition radiation spectrum and an autocorrelation technique.

1 INTRODUCTION

Transition radiation is one of the radiation phenomena which are connected to a homogenous motion of a charged particle. In this case the inhomogenity of the matter the particle passes through is responsible for the emission of the radiation. This phenomenum was predicted by

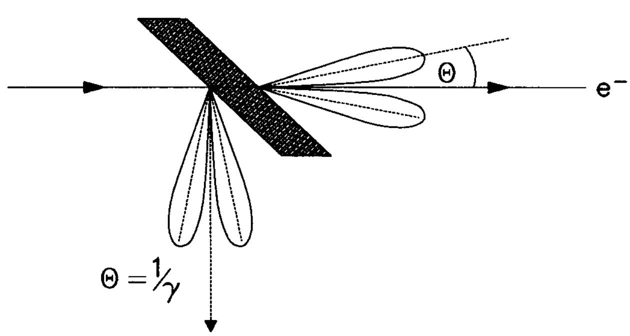

Figure 1: Transition Radition from a single foil inclined by 45° with respect to the beam direction.

I.M.Frank and V.L.Ginzburg [2] in 1946 and experimentally confirmed in the following years. The application of transition radiation for beam diagnostics in particle accelerators was first demonstrated in the pioneering work by L.Wartski [3]. The physics of transition radiation is well established within ordinary electromagnetic theory [4, 5, 6]. A charged particle crossing a single boundary emits transition radiation in the backward and the forward hemisphere of the boundary. For relativistic particles the radiation is emitted in a small cone with an opening angle of $1/\gamma$ due to the Lorentz contraction as shown in fig.1 for the case of a single foil inclined by 45° with respect to the beam direction. For a single electron with $\gamma >> 1$, passing through a material with plasma frequency ω_p, the intensity distribution of the radiation emitted into vacuum is given by [6] ,

$$\frac{d^2W}{d\omega d\Omega} = \frac{\alpha}{\pi^2}\left(\frac{\theta}{\gamma^{-2}+\theta^2+\left(\frac{\omega_p}{\omega}\right)^2} - \frac{\theta}{\gamma^{-2}+\theta^2}\right)^2 . \quad (1)$$

where α is the fine structure constant , γ the Lorentz factor , θ the emission angle and ω_p the plasma frequency. This is shown in fig.2 for different energies while in fig.3

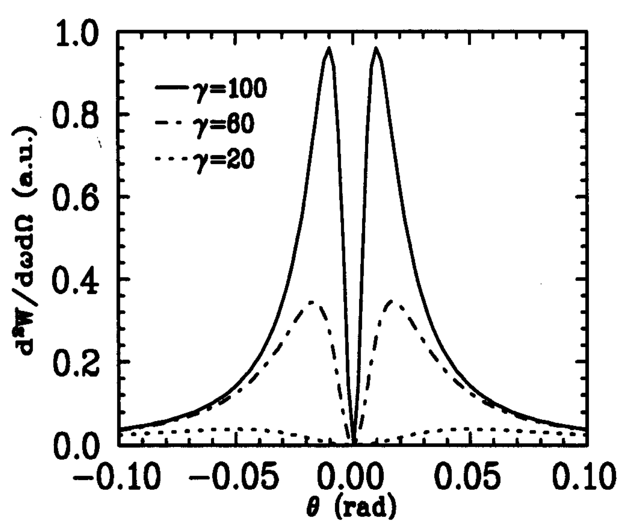

Figure 2: Spatial distribution of transition radiation for different electron energies.

the calculated spectrum is plotted which was obtained by intergrating over $d\Omega$. The total emitted intensity is proportional to γ and the plasma frequency of the material.

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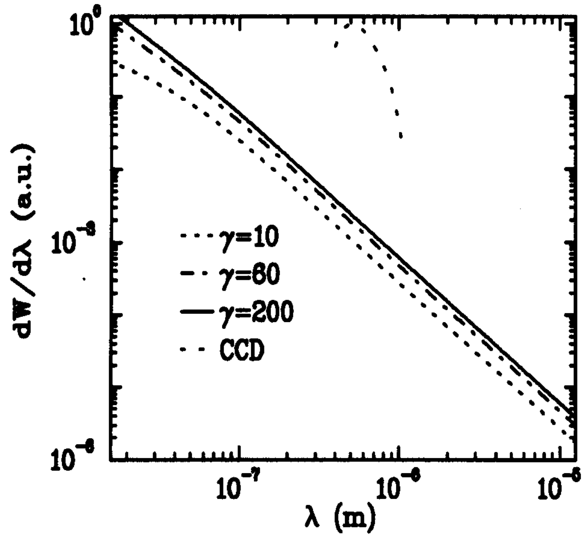

Figure 3: Spectrum of transition radiation for different electron energies and response function of a standard CCD camera.

2 TRANSVERSE DIAGNOSTICS

2.1 Experimental Setup

Presently there are eleven OTR diagnostics stations installed at the S-DALINAC electron accelerator. Each station consists of a remotely controlled pneumatic driven aluminum target which can be inserted into the beam to initiate the emission of transition radiation. As shown in fig.4 the target is inserted under 45° to allow the light detection under 90° with respect to the beam direction through a vacuum window. So far the system is used for transverse diagnostics at energies from 250 keV up to 86 MeV. To obtain a reasonable image a beam current of 500 nA is needed at 250 keV and as little as 2 nA at 86 MeV. The target material is 25 μm thick aluminum foil with a plasma frequency of 33.9 eV, successful tests were also performed with silicon targets and mylar foils. The commercial CCD cameras from Panasonic (WV-BL600) and EHD (Kam 02) which were used for detection are equipped with standard f = 50 mm optics. The minimum intensity needed for these cameras is 0.05 candela , their spectral sensitivity is also shown in fig.3. For digitizing , a framegrabber from Matrix Vision is used which is able to digitize in realtime with 8 bit resolution. The framegrabber is installed in a PC for data acquisition and controlling. The full two dimensional intensity distribution of the grabbed beamspot is finally processed and displayed using IDL [7], a practical graphical data processing tool on a fast VAX type workstation. Several routines allow the operator of the accelerator to extract beam profiles, radii, emittances and other beam parameters.

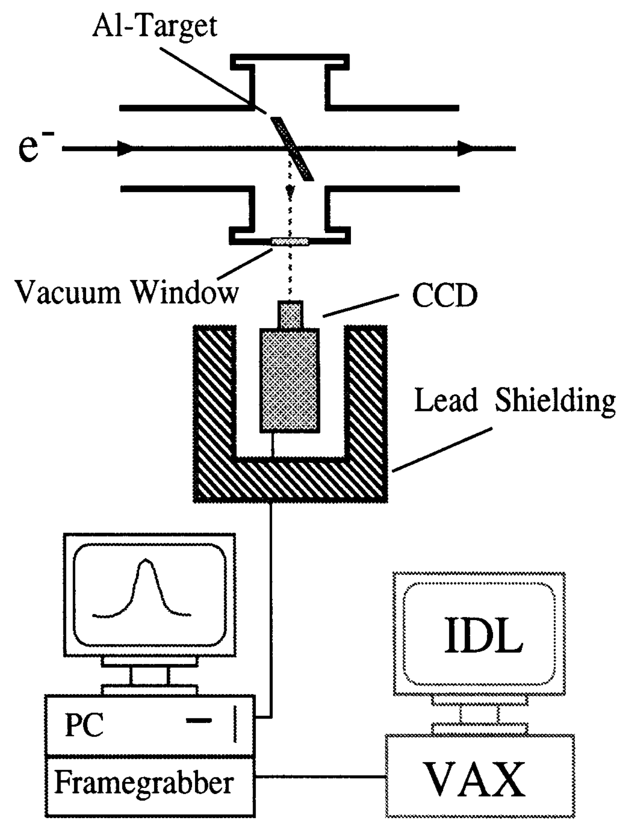

Figure 4: Schematic setup of an OTR diagnostics station.

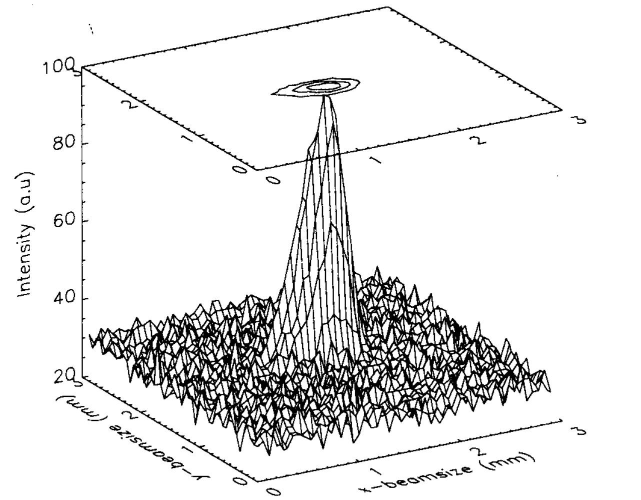

Figure 5: Example of a surface and contour plot of a grabbed beam spot image.

2.2 *Analysis and Results*

The OTR diagnostics system is used routinely to measure the complete set of transverse beam parameters. The first step of processing is to display the two dimensional intensity distribution giving the operator more information than a simple video image , but even the spot image itself gives a more reliable impression of the beam than images from standard viewscreens. Figure 5 shows an example of such a distribution which is available for the operator almost online. From these distributions beam profiles can be extracted and the beamsize can be determind by a fit assuming a Gaussian shape of the profiles. The resolution is, depending on the optics, about 30 pixels/mm , typical one σ beam radii are 0.5 mm. To determine the complete σ matrix for emittance measurements two different methods were used: The three-

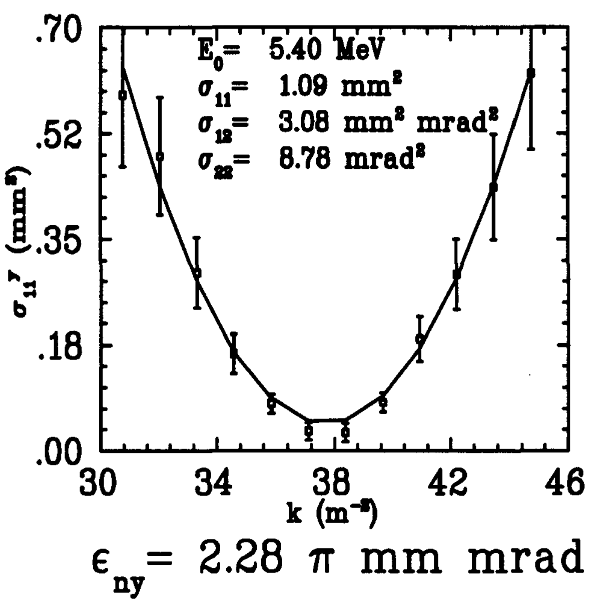

Figure 6: Example of an emittance measurement with the three-gradient method. The determination of the vertical σ matrix is shown.

gradient method needs several pictures to be taken from the same screen at different quadrupole settings. The sigma parameters are found by fitting a quadratic form to the measured beam sizes. An example of such a measurement is presented in fig.6. The normalized emittances were found to be $\epsilon_{nx} = 0.94\ \pi\ mm\ mrad$ horizontal and $\epsilon_{ny} = 2.28\ \pi\ mm\ mrad$ vertical. The measurement was performed at an energy of 5.4 MeV with a current of 500 nA and a 3 GHz cw time structure. The beam parameters could be found by fitting within an accurancy of 15 %. The second method we used is the three-target method , three beam sizes where measured on three screens at different locations in a straight section of the beamline.

3 LONGITUDINAL DIAGNOSTICS

3.1 *Energy Spread Determination*

The system described above could be used without any hardware modifications to determine the energy spread in a dispersive section of the beamline. The energy distribution in the beam is projected onto the dispersive axis and the beam profile contains the energy spread information , taking into account the intrinsic beamsize. A routine was developed to calculate and display online the energy spread of the beam from these OTR measurements. The system is calibrated by a field measurement of the dipole magnet causing the dispersion. An example of a beam profile and the resulting fit , assuming a Gaussian energy distribution , is shown in fig.7 giving an energy spread of (0.11 ± 0.05) % FWHM.

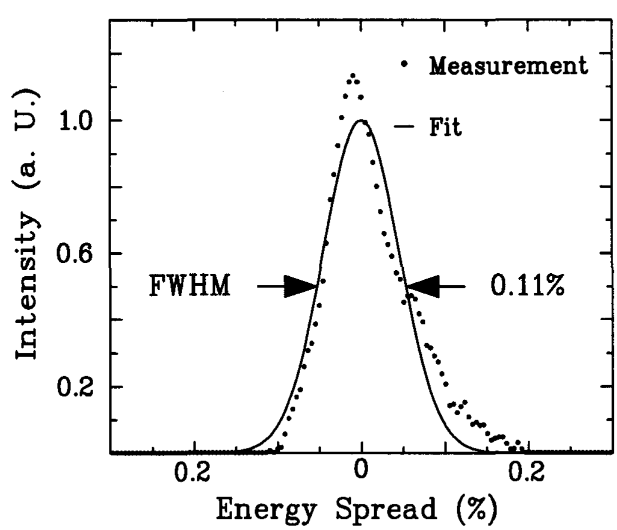

Figure 7: Energy spread determination from a beam profile measurement (background subtracted) in a dispersive section.

3.2 *Bunch Length Measurement*

The bunch length measurement with transition radiation [8, 9] makes use of the very long wavelength regime of the emitted radiation. In this region the radiation becomes coherent because the bunch length is comparable with the wavelength. Therefore an autocorrelation technique could be used to measure the bunch length in the picosecond range. The setup is shown in fig.8. The radiation is extracted through a PE-window , autocorrelated in a michelson interferometer and finally focused on a pyroelectric detector to measure the power as a function of the mirrorposition in one interferometer arm. With this method it is possible to obtain the bunch length but not the exact bunch shape because the phase information is lost through the power measurement. Nevertheless, with

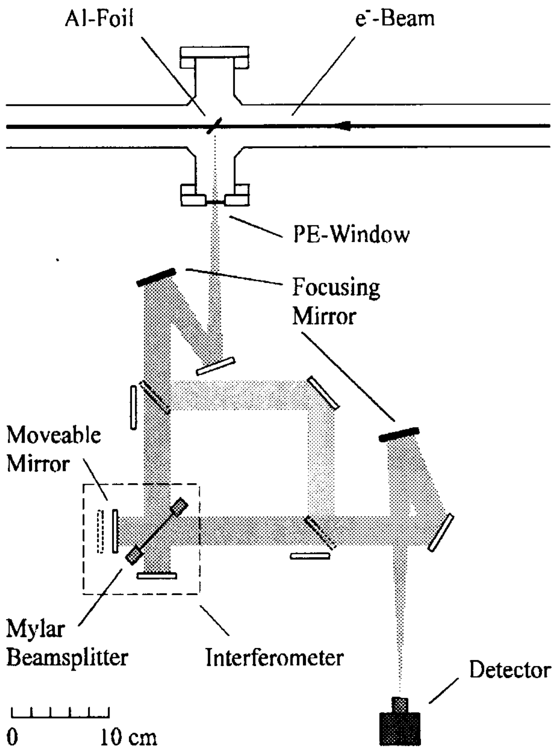

Figure 8: Autocorrelation setup for the transition radiation bunch length measurement.

the help of a rather sophisticated and delicate fitting procedure it is possible to find the most likely bunch shape. The procedure starts with an assumed bunch shape , calculates its power spectrum after autocorrelation and compares the result with the measurement , taking into account various absorption and interference effects as well as the spectral response of the detector. The procedure is described in detail in reference [10]. The measurement was performed during an FEL-run with an electron beam energy of 31.2 MeV , a bunch repetition rate of 10 MHz and a macropulse of 1 ms duration with a repetition rate of 33 Hz at an average current of 40 μA. The measurement yielded a bunch length of (4 ± 0.25) ps and a most likely rectangular shape.

4 CONCLUSIONS

Beam diagnostics using transition radiation has proved to be a comfortable and cost efficient alternative to viewscreens , wire scanners and SEM grids. The instantaneous and linear response over a wide range of currents and energies makes OTR preferable to viewscreens and could be summarized with the computer language expression 'What you see is what you get'. Standard CCDs connected with commercial framegrabbers are fast and variable detector systems , providing the full two dimensional intensity distribution , impossible to obtain with wire scanners or grids. In combination with graphical data processing , OTR diagnostics becomes a very helpful and simple to handle tool for the accelerator operators. Finally , as indicated by the bunch length measurement , the potential of transition radiation as a diagnostics tool for particle accelerators is not yet fully explored.

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