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Beam characteristics control using Optical Transition Radiation (OTR)

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BEAM CHARACTERISTICS CONTROL USING OPTICAL TRANSITION RADIATION (OTR)

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ABSTRACT

The automatic control and optimization of high intensity particle beams requires an instrumentation operating rapid physical phenomena associated to performant electronics and acquisition processes. Since some years we have been using Optical Transition Radiation (OTR) on various electron machines (TTF–DESY, Orsay, Frascati) in order to measure beam characteristics as position, transverse profile (providing transverse emittance and energy dispersion), angular pattern (providing divergence, energy and energy dispersion), bunch length. The relative energy range extended from $\gamma = 3$ to 4000. The acquisition of the optical informations required use of suitable CCD and Streak Cameras associated to performant digitizers, efficient image processing and analysis programs. Different velocities of acquisition have been obtained depending on the degree of accuracy and level of Signal/Noise required and on the kind of parameters to be measured (energy dispersion, emittance). Owing to this experience we can consider the introduction of the set of beam parameters provided by OTR in a control procedure like ABS (Automated Beam Steering and Shaping).

1. INTRODUCTION

Prompt beam diagnostics are necessary to ensure automatic control for optimization and stabilization of the beam. This is particularly needed in linacs and transfer lines to or from circular machines, where rapid recuperation of the beam qualities is needed for stable operation of the accelerator. The requested rapidity concerns the physical phenomena associated to the observation, the acquisition system with its hardware and software components and the eventual feedback on the beam.

LAL–Orsay and INFN–Frascati have used various kinds of diagnostics on their installations. Among them, diagnostics using electromagnetic radiation in the optical range, as Optical Transition Radiation (OTR) and Cerenkov Radiation have been operating on their machines as well as on the Tesla Test Facility (TTF) at Hamburg[1]. Longitudinal profiles, extracted from the Cerenkov image of the beam at the entrance of a Streak–Camera, allowed bunch length determination with a resolution comprised between 1 and 2 picoseconds[2]. Transverse profiles, provided by the OTR image of the beam, permitted the determination of the transverse emittance as well as of the energy spread. Additional information on beam divergence was also reachable, using OTR imaging at infinity. The spatial resolution concerning the OTR images of high energy electron beams, having submillimeter transverse dimensions, has been studied experimentally[3] and theoretically[4,5]. The results showed that, considering the FWHM values of the beam profiles, no redhibitory limit had to be considered at high energy, contrarily to some wrong expectations[6]. Henceforth, OTR appears as a powerful tool for beam diagnostics providing all the needed informations to determine the six–dimension emittance of a beam, even at high ultrarelativistic energies ($\gamma > 10^4$). Hereafter, we present the main features of the OTR, describing its capabilities in beam diagnostics with the attached acquisition tools. Analysis of the performances of OTR diagnostics will allow us to answer the question of its use in ABS configuration precising the kind of control we can reach with its present development.

2. PHYSICAL BACKGROUND

When the field distribution of a charged particle, moving on a rectilinear trajectory at constant velocity, is perturbed by external causes (changes in boundary conditions, variation of the dielectric properties in the medium,...) an electromagnetic radiation is emitted to ensure the continuity of the field itself. A broad class of phenomena can be explained by this simple physical principle; but for historical reasons they have different names and often different mathematical approaches.

Transition Radiation is one of these phenomena and refers to the radiation emitted when a charge in uniform motion crosses a sharp boundary between two media with different dielectric properties. It is essentially a surface effect and for this very fast, in the picosecond or sub-picosecond range. This radiation has been extensively studied, mainly for its use in elementary particle identification; its intensity, in particular in the UV and soft X range, being proportional to the particle energy.

In the years between 1972 and 1975, L. Wartski demonstrated that Transition Radiation in the visible spectrum (OTR) was a very useful tool for electron beam diagnostics[7]. Its practical use was only limited by the low intensity of the radiation and the relatively poor sensitivity of the imaging devices at that time.

At present, the basic principles of these diagnostics, with few refinements that have clarified the limits at very high energies, are still as proposed by L. Wartski, but the technical development of imaging devices allows its widespread use, even for heavy particle beams.

From the physical point of view, the Transition Radiation is emitted by the rearrangement of charges or atomic polarization vectors on the surface due to the passage of the electromagnetic field of the particle. For an incidence normal to the surface, OTR is emitted symmetrically forward and backward around the particle direction of motion. The radiation is radially polarized, so for symmetry reason, it has zero intensity along the axis and a maximum on a cone at an angle equal to $1/\gamma$; γ being the relativistic factor of the particle. It must be noted that roughly only 10% of the total intensity is contained inside this cone. For a non normal incidence, the forward radiation is still emitted around the direction of the particle, while the backward radiation is now emitted around the direction of specular reflection. The distribution is asymmetric around this axis; the asymmetry almost disappearing at high energies.

An intuitive picture, that helps to understand, is to consider the backward OTR as the reflection from the surface of the virtual photons which constitute the particle field in the Weisacker–Williams approximation[2]. The derivation of the angular distribution of the radiated intensity, in the general case of a particle crossing at an arbitrary angle the surface separating two different media, is rather cumbersome. A great simplification is obtained when assuming an ultrarelativistic particle moving in vacuum and crossing an infinite perfect metallic surface at an angle of 45 degrees. The backward emission is around an axis perpendicular to the particle velocity direction. For enough high energy ($\gamma > 200$), the radiation is symmetric around the central axis and is radially polarized. It presents a flat intensity spectrum and the intensity for the angular distribution is given by:

$$\frac{\mathrm{d}W}{\mathrm{d}\Omega\,\mathrm{d}\omega} = \frac{e^2}{c\,\pi^2}\frac{\beta^2 \sin^2\theta}{\left(1-\beta^2\cos^2\theta\right)^2} \tag{1}$$

For a real metal, as suggested by the model of virtual photons, the previous distribution must be multiplied by the appropriate Fresnel reflection coefficient. For high energy and good metals this leads to a small decrease of the absolute intensity, with irrelevant modification of the angular distribution, at least in the optical range.

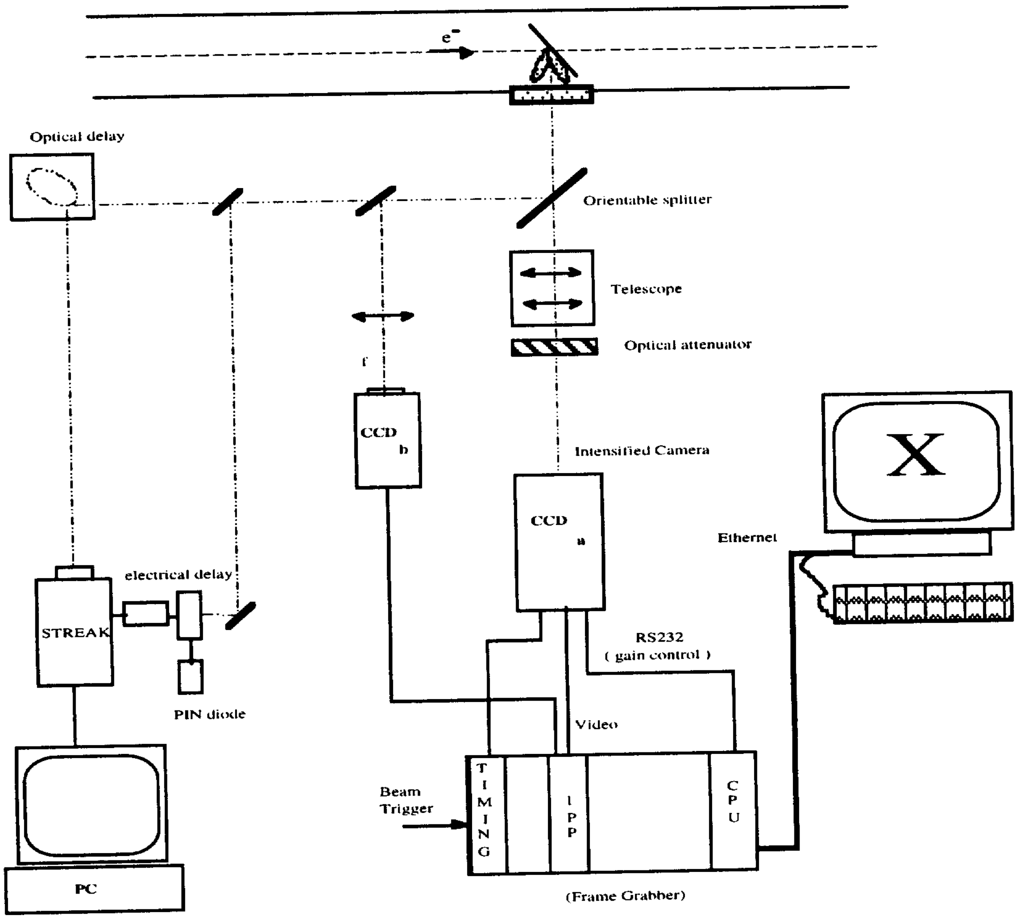
The directivity of OTR and its energy dependence are the main advantages of this diagnostics compared to standard fluorescent screens. The measured radiation intensity is the convolution of the single particle distribution, with the angular and energy beam distributions.

3. OTR AS AN INSTRUMENTATION TOOL

At first analysis, Transition Radiation presents many advantages even for applications, as beam imaging, where well established methods of observation, like fluorescent screens, have been used for many years as a standard tool for accelerators. We shall show how the Transition Radiation can give clear informations about the particle beam characteristics.

Examples, which will be given, are mainly based on our experience on electron machines since the most relevant parameters as the beam current (i.e. total beam charge within integration time of the CCD Camera) and the energy (Lorentz factor) can be easily resized when evaluating applications for proton machines.

As OTR is a destructive diagnostics we consider its use exclusively in linacs and transfer lines. For high enough beam energy and considering relatively thin radiators (10 to 20 micrometers), OTR measurement can be operated during the running–in of the machine. All the beam parameters will be determined using the backward transition radiation for which a typical scheme is presented on figure 1. After describing the measurement possibilities brought by OTR we shall mention the main features of the material needed for that.



Sketch of the longitudinal and transverse beam profile measurements using OTR
CCD a : beam dimensions
CCD b :beam divergence

Figure – 1. Setup of OTR Measurements

3.1. *OTR measurements*

3.1.1. Beam transverse profile

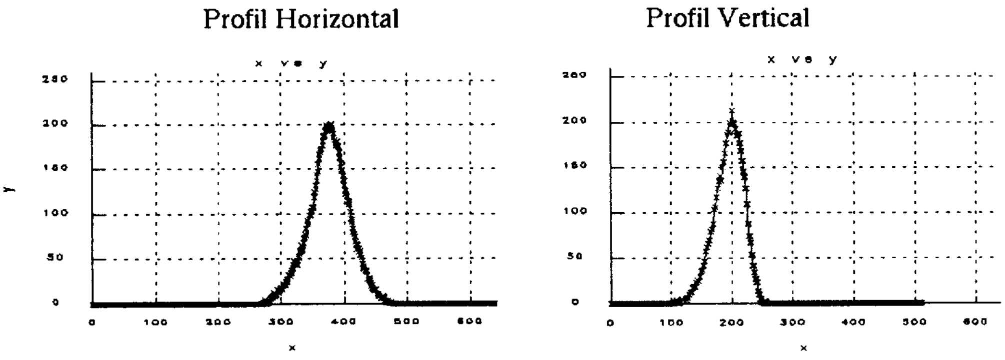
Beam profile can be simply obtained by means of a Video CCD Camera with an objective focusing on the saurce of radiation, i. e. the metallic foil hitted by the beam. If needed, an optical system can be used instead of the simple objective and, in both cases, a calibration (pixels/mm) has to be worked out using the classical methods.

The use of OTR constitutes an improvement in the beam imaging methods with respect to the fluorescent screens, more sensitive, but presenting problems of saturation and persistency. However, concerning OTR, besides the limitations associated to the lower sensitivity (some 10^{-3} photons/e- as total yield) the dependence of the angular distribution with energy makes the choice of the collecting optics more critical, mainly for low energies; the aperture of the light cone, defined by the maxima, is 2/gamma. Though this definition of aperture is quite restrictive, more particularly for the diffraction considerations, it is often convenient as it gives a simple idea of the variation of the OTR angular distribution with particle energy.

For high charge and/or long macropulse beams, this limitation will, of course not be actually significant. Moreover, the light intensity, being large enough, neutral filters have to be inserted in order to avoid the saturation of the CCD sensors. CCD cameras with remote gain control will give higher flexibility.

The video image on the CCD is numerized and profiles obtained by cutting the image by horizontal/vertical lines provide the characteristics as the FWHM, RMS width, the widths corresponding to 50 and 90% of the intensity. An example of transverse profile is given on figure 2.

The transverse profiles can be used to determine the beam position, the transverse emittance and the energy spread.


Profil Horizontal

Profil Vertical

Figure – 2. Transverse profiles

- Beam emittance

Emittance measurements in linear accelerators or transfer lines are based on profile measurements. Standard methods allow the determination of the beam matrix[8] from the beam profiles at three positions along the beamline or at a single position performing quadrupoles scanning in order to obtain the three coefficients of the beam emittance ellipse as a result of a fit when using n quadrupole strengths and the corresponding beam widths. The latter is called as the "Three Gradient Method" and is more often used.

An automatic procedure can be foreseen in such a way:

- at each quadrupole setting, m measurements of the transverse profile are worked out. An average value is then determined: the consequences of beam fluctuations are henceforth minimized. m is about 10
- n quadrupole settings are chosen and the corresponding beam widths are acquired. n value should be comprised between 10 and 20.
- a least square fitting is operated on a series of expressions associating the measured widths with the TRANSPORT coefficients of the optical channel and the three coefficients of the emittance ellipse.

Generally, a thin lens approximation is operated for the optics. However, in some particular cases, where the geometrical conditions do not allow such approximations, the actual parameters of the quadrupoles are used and a minimization procedure, like MINUIT, can be used. That was the case for the measurements on TTF[2].

- Energy dispersion

An OTR radiator put in the horizontal focal plane of an analyzing magnet provides an horizontal beam size proportional to the energy spread. This constitutes a very convenient way to measure the energy spread.
Application of OTR diagnostics to Energy Dispersion by means of a dispersive section measurement must be done with some care. To maximize the sensitivity of the magnetic spectrometer the dispersion coefficient of the latter must be as large as possible. But, in that case, in addition to a decrease of the photon density on the image, cares on the optical acceptance of the detecting system must be considered due to the directivity of the radiation itself.

- Beam position

The knowledge of the beam position can be considered as a by-product of the beam transverse profile as the beam barycenter can be exactly evaluated from the beam image spot.

3.1.2. Angular pattern

Angular pattern measurement is probably the most interesting TR diagnostics because it contains a large amount of informations about the beam. Angular pattern of TR radiation coming from a particle beam is the result of the convolution of the single particle pattern with their energy and divergence distributions.

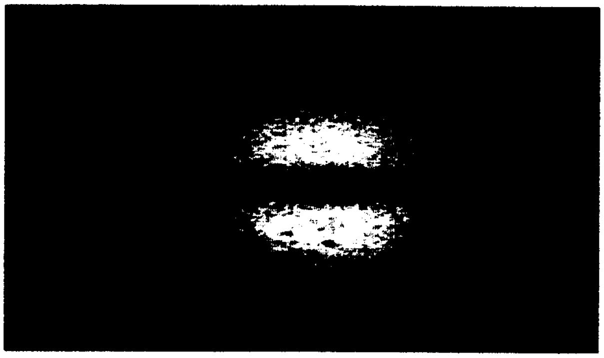


Figure -3- Angular pattern (after a beam splitter)

- Beam divergence

  As shown on Fig. 3 the angular pattern resulting from the superimposition of the OTR emitted from two or more particles impinging on the metallic foil with different, angles will have a central minimum different from zero and a somewhat larger distribution. Besides the standard methods previously listed, a very promising technique for single-shot emittance measurement is given by TR when beam profile and angular pattern can be simultaneously measured at a given place on the beam line (see Figure 1). This will result in a measurement of the beam transverse size and its RMS divergence from which emittance can be calculated.
  The radiation from the metallic foil is driven to two CCD cameras by means of a beam splitter. One of them is focused on the source of radiation while the other is focused at infinity to get the angular pattern.

- Beam energy

  The OTR angular distribution provides a way to measure the beam energy in regions where no dispersive sections are present. The beam energy value is obtained from the measurement of the angular width corresponding to the separation of the two maxima on the angular profile (twice the value $1/\gamma$) .
  Using interferences between two radiators (Wartski Interferometer) one could improve the energy determination[7].

3.1.3. Time resolved measurements

- Using a gated intensified CCD camera it is possible to get the beam profiles at different locations inside the beam macropulse. This technique may be useful for the beam dynamics analysis when studying for instance the longitudinal and transverse effects of the wakefields. Such analysis has been currently realized at the TTF by Orsay and Frascati groups[2,9].

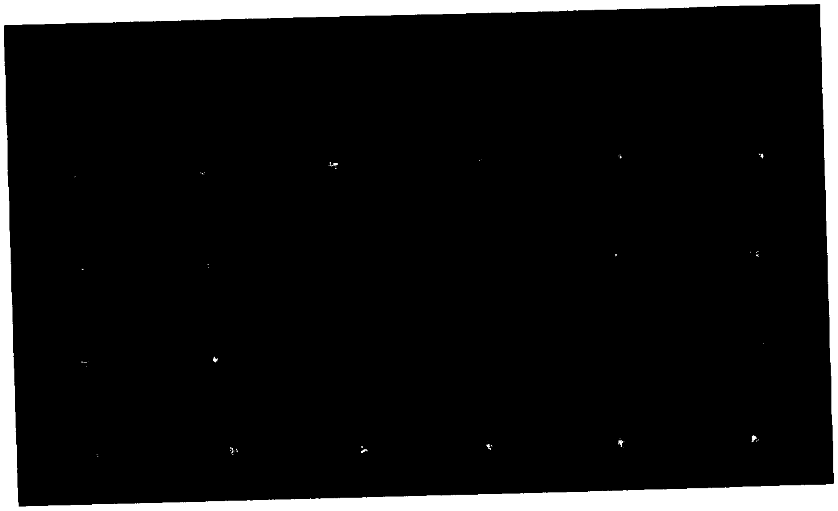


Figure – 4. Beam spots at differents locations inside a macropulse

- The OTR image sent to a Streak–Camera through an appropriated optics can provide the informations on the bunch duration. The main problem is to guarantee a sufficient number of OTR photons, for a microbunch, at the entrance of the Streak–Camera.
  On Figure 5 we present the images obtained on the Streak–Camera for the TTF bunch, using the Cerenkov radiation which provided more photons / microbunch than the OTR for 30 pCb.

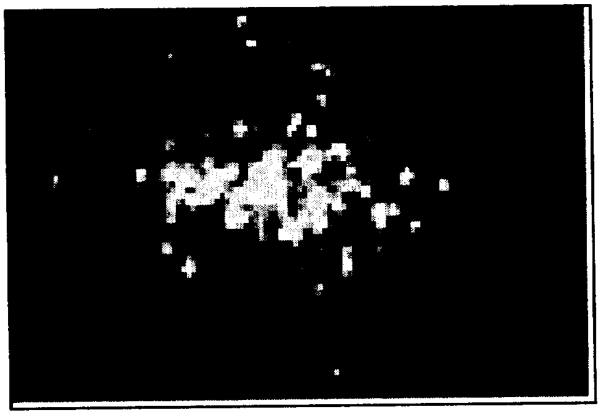


Figure – 5. Image of the beam on the streak camera (Cerenkov)
Time in on the vertical scale

3.1.4. Spectrum analysis

Bunch length measurement by means of Spectral analysis is a very promising method especially for ultra-short bunches produced by the linacs for FEL and linear colliders. Spectral analysis of the radiation emitted from the beam is realized with millimeter/microwave interferometer and the resulting spectrum evidences the range of wavelengths where the contribution of every particle add coherently, i. e. for wavelengths shorter than the bunch length. The spectral intensity emitted by a bunch of N particles is given by:

$$I_T(\lambda) = I_1(\lambda) \,.\, [N + N(N-1)\,|f(\lambda)|^2] \qquad (2)$$

where $I_1(\lambda)$ is the intensity radiated by a single electron at the given wavelength and $f(\lambda)$ is the bunch form factor which can be expressed (neglecting the transverse charge distribution) as a function of the longitudinal charge distribution only.

$$f(\lambda) = \int_{-\infty}^{+\infty} \rho(z)\, e^{\left(\frac{2\pi i z}{\lambda}\right)} \, dz \qquad (3)$$

At wavelengths much shorter than the bunch length the form factor vanishes while at wavelengths of the order or longer than the bunch longitudinal extension the coherent part of the spectrum is much more intense than the incoherent part and the form factor can be extracted. Finally, the bunch shape is obtained by inverse Fourier Transform.
An example is given below. { See Figure – 6 }

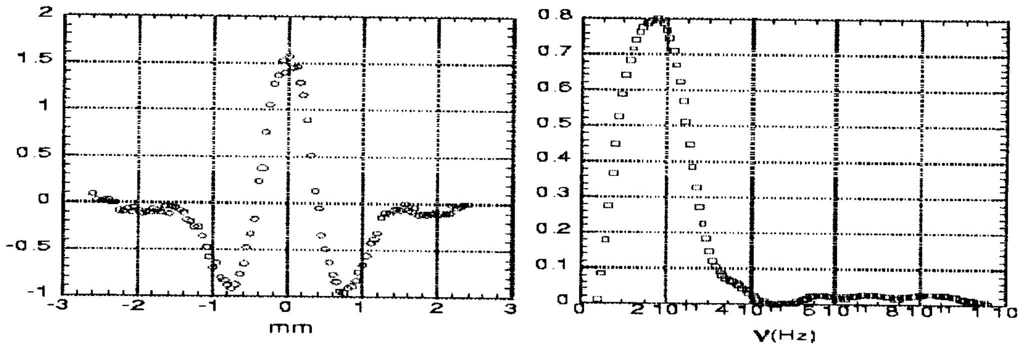


Figure – 6. Spectrum measurement for bunch length determination

A simplified version of this set–up can be used to obtain a relatively fast measurement of the bunch length; this could serve, for instance, for the optimization of the bunching system (sub-harmonic buncher and longitudinal compressor in TTF). In fact, the output signal on the detector, representing the radiation intensity integrated over its bandwidth (or at a selected wavelength), will become higher as shorter becomes the bunch length because larger will be the portion of the spectrum giving a coherent contribution.

3.2. *Instrumentation*

This concerns mainly the optics used to collect the radiation, which could be different if we use CCD or Streak Cameras, and also the acquisition system to digitize beam images.

3.2.1 Optics

The most used geometrical optics concerns telescopic mountings ensuring a simple and reliable transformation ratio between object and image. In order to increase the light intensity it is useful to work with a wide bandwidth but this requires the use of achromatic lenses in order to keep a good transmittance and quality for the image.

Available codes help in verifying and optimizing the optical beam transmission through the lenses. This is of particular importance when trying to keep enough photons (for a microbunch) at the entrance of the Streak-Camera[2].

3.2.2. Electronics & Software

The choice of electronics is usually made together with the software and depends mainly on the kind of measurement, on the performances needed and the control system environment since for some automatic procedure (e.g. emittance measurement) it is useful to have an easy access to the control of the accelerator components. For our application we followed two different approaches.

The first one is a Client/Server application. The graphic interface is created, for instance, with OnX, which is an XWindows/Motive application builder developed by LAL, as the communication library, under TCP/IP, named Cm which permits data exchange with the program controlling the acquisition. This program is running under VxWorks using the frame grabber library to control the hardware. It acquires m images (here, 10) in memory for each working point. The analogic video output (CCIR) of the CCD camera is 8 bits digitized with a frame grabber which can be in VME standard and connected to the CPU board by the VME bus. The memory extended to 32 Mbytes allows the acquisition of m images (10 for our application) for each working point in order to get enough statistics before sending the images to a workstation (here, SunOs); the latter allows saving images and serves for the user graphic interface.

The second one is a stand–alone PC based (Macintosh in this particular case) control and acquisition system. Two computers are used: one is the operator console, the other has the control of the I/Os (remote optics movements, video MPX, etc.) and the built-in Frame Grabber. The operator sends commands from the console using graphic interface based on LabVIEW and follows their execution on a monitor display[10.]. The two computers, and the local CPU of the accelerator control system exchange information via shared memory in a VME environment. Macintoshes access the VME using a fiber optic link to optimize the velocity for the image transfer and to avoid overloading of the network. Communication among the parts, the two Macs and the accelerator's control system, is ensured by mailboxes on the local shared memory with full client/server functionality. A second Frame Grabber controls an intensified camera for low intensity and time resolved measurements. During the measurements all image files are stored in the console hard disk in order to provide complete information for off–line analysis.

The software we developed can be divided into three main categories: filtering software, image analysis and measurements.

The software filters are used to prepare images for analysis removing undesirable background and noise mainly due to X rays impinging on the camera even if it is usually shielded against radiation with lead or tungsten plates. Because shielding the camera does not prevent from X rays coming from the metallic foil we developed a procedure which scans the image removing spikes while the beam spot is kept untouched. This demonstrated to be more efficient than the image frequency filtering.

To determine the beam barycenter we take 2 (2xm, more precisely) profiles (one horizontal, the other vertical) or projections of the beam. The widths of resulting distributions are evaluated at/for:

- 50% of the integrated intensity,
- 90% of the integrated intensity,
- Full Width Half Maximum (FWHM),
- RMS.

The other source of errors, beam fluctuations, being eliminated by using enough statistics (m) for each working point; we can then get position and size minimizing the errors. Our experience shows that for better performances and higher reliability of the results, a fine tuning of the analysis software is required. This suggests the execution of customized analysis procedure on local hosts (PC or VME CPU) which allows a higher degree of freedom for the implementation of the software and for the configuration of the analysis routine to that particular set of images. It is also important, especially if the images present differences on the noise level, to keep the possibility of controlling the procedure during the execution.

For the emittance measurement the most relevant software development was towards a realization of a full automatic implementation of the previously described procedure. Although the total time needed for the measurement depends strongly on the required accuracy and on the overall quality of the beam image (noise and fluctuations) we can estimate an execution time between 15 and 20 minutes for the emittance determination.

4. PERFORMANCES

4.1. Resolution

The ultimate physical resolution, when using CCD, is given by the dimensions of the pixels, comprised for both dimensions between 8 and 20 micrometers. The accuracy of the measurement of beam physical parameters, like position and profile widths, depends obviously on the optical magnification and as the result of a statistical distribution over many pixels, can be in principle better than the pixel size; this is normally verified for the beam position.

In a normal environment we have to take into account the contribution of the frame grabber and of the optics and the actual resolution is obtained by the determination of the Modulation Transfer Function (MTF). It depends on the (intensified) CCD sensitivity. In our case, the MTF provided a value of 70 micrometers. {See Figure 7, for the sketch of MTF}. For the angular pattern the image dimension is dependent linearly on the focal length; a compromise can be found between the spatial resolution and the S/N ratio.

For the energy measurement, the accuracy of the distance between the two maxima is similar to that associated to the profile measurements. For small beam divergences the angular pattern is close to that associated to the single particle and the deconvolution can result quite imprecise, especially with noisy pictures. This put a practical limit on its application. In particular it has been estimated that a beam divergence (RMS) representing a value lower than 15% of the half angle radiation cone could not be measured by this way.

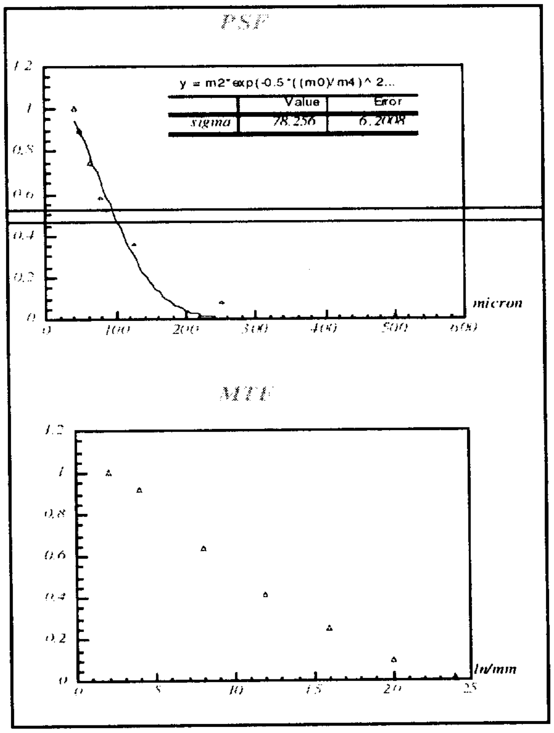


Figure – 7. Point Spread Function (PSF) and Modulation Transfert Function (MTF)

4.2. *Velocity*

A beam position and size (H & V) measurement requires 1 to 2 seconds if a filter is used and much less if not. Concerning the beam emittance, the overall measurement which concerns 2.n.m profiles (200, at least in our case) takes some minutes (less than 20).

5. SUMMARY & CONCLUSIONS

The OTR allows the measurement of characteristics leading to the determination of the 6–D emittance and position of particle beams. Recent measurements at TTF showed also the possibility of getting fine analysis of the beam characteristics inside a macropulse permitting, hence, studies on beam dynamics. The OTR, associated to good quality optics and performant acquisition tools, allows an almost on-line control of the beam characteristics. The absence of energy threshold, contrarily to the Cerenkov radiation, makes it useable for beams of some eV, as already demonstrated by Mahan and Gallagher[11]. The upper limit being brought by diffraction; recent theoretical and experimental studies showed that no redhibitory limit was met at " γ-λ " values[3,4,5,12].

The rapidity of the radiation phenomenon, in the sub–picosecond range, makes it useable for short bunch measurements.

Concerning an eventual steering using OTR, the position and size measurements, being in the second time range, can be considered for beams of moderate intensity. The bunch length determination, requiring more time, can only be integrated in a checking procedure. However, recent progresses in that field brought improvements in the adjustment of the optics as in the automatic peak search in the streak mode[13].

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