A Review of Optical Diagnostics Techniques for Beam Profile Measurements.

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Abstract

The measurement of beam profiles using optical detectors is widespread. This paper reviews the various optical techniques employed in the community and points out the advantages and disadvantages for each one, illustrated by practical examples including experience with systems at the Daresbury SRS. Fundamental imaging limitations will be discussed together with calibration methods.

1. INTRODUCTION

In every particle accelerator the beam profile is an important parameter. Many methods exist for determining the beam profile, including several destructive techniques. This paper deals only with methods which rely on emitted visible synchrotron radiation from bending magnets as the diagnostic means. A review of the imaging resolution is given, followed by a discussion of optical detectors in use in the accelerator community. Possible calibration methods are also highlighted.

2. IMAGING RESOLUTION

The resolution of profile measurements by synchrotron radiation (SR) is strictly limited by fundamental effects. It is important that these effects are minimised so that the best resolution is obtained for the profile measurement. The horizontal and vertical cases are not the same; they are dealt with separately below.

2.1 Horizontal Case

2.1.1 Chromatic Error

In precise optical imaging of SR it is necessary to monochromate the light. This is most easily achieved with a bandpass filter. Typically a filter with a 500 nm centre wavelength and 30 nm bandwidth is used. However, as will be shown later, shorter wavelengths will improve the resolution.

2.1.2 Depth of Field Error

By its very nature the electron beam is a long source of light. This means that the imaging of the SR will produce a significant depth of field error, dependent upon the acceptance angle. For the simple case, illustrated in figure 1, the depth of field error is given by:

$$\Delta_{df} \approx \frac{L}{2}\theta \qquad (1)$$

where L is the length of the source and θ is the half-acceptance angle. Note that L is given by:

$$L \approx 2R(\theta + \Psi_{SR}) \qquad (2)$$

where R is the electron orbit radius and Ψ_{SR}, the natural opening angle of the photon beam, is given by:

$$\Psi_{SR} = \left(\frac{3\lambda}{4\pi R}\right)^{1/3} \qquad (3)$$

for the case where λ, the wavelength of the light, is much longer than the critical wavelength. This is usually the case for visible wavelengths. Note that Ψ_{SR} is the same in both planes.

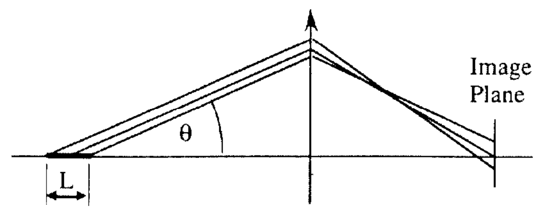

Figure 1. Depth of field error sketch.

2.1.3 Diffraction Error

Any imaging problem that involves apertures will inevitably have a diffraction error. Contrary to the depth of field error in the previous section, this error increases as the aperture is decreased. It is usual to restrict the aperture with either a circular iris or a vertical slit. The formulae for the diffraction resolution for these two cases are given below [1]. For an iris,

$$\Delta_{diff} = 0.61\frac{\lambda}{\theta} \qquad (4)$$

and for a slit,

$$\Delta_{diff} = 0.5\frac{\lambda}{\theta}. \qquad (5)$$

Clearly, a vertical slit will give the better resolution.

2.1.4 Curvature Error

Due to the nature of the source, the curvature of the electron beam also contributes an error term that limits the horizontal resolution. From the geometry shown in figure 2 it is straightforward to derive the apparent width of the source as:

$$\Delta_{curv} \approx \frac{R\theta^2}{2}. \qquad (6)$$

So, for a particular wavelength, the best resolution is found by minimising the sum of the squares of the three error terms described in equations (1), (5) and (6). For the SRS with R = 5.5 m, Ψ_{SR} = 2.8 mrad and λ = 500 nm, the optimum value of θ is 2.6 mrad, defined by a vertical slit. This gives a combined value of 125 μm for the apparent width of a negligible cross-section beam.

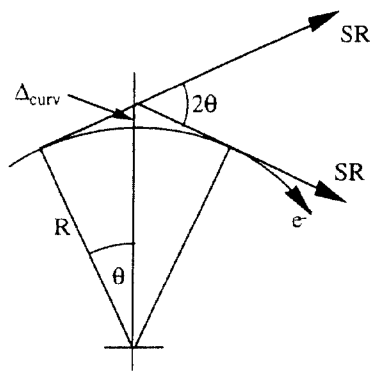

Figure 2. Curvature error sketch.

2.2 Vertical Case

For the vertical case the chromatic and depth of field errors are as for the horizontal. However, in the horizontal case the relevant diffraction effect and the depth of field error were both in the same plane. This is not true for the vertical case. Here the depth of field is again determined by the horizontal acceptance, but the diffraction is now only of consequence in the vertical plane. This means that the horizontal acceptance must be set to limit the depth of field and that any vertical acceptance limit will introduce unnecessary broadening due to diffraction. Therefore, in the vertical plane it is most advantageous to use a vertical slit instead of a circular iris. The minimum diffraction error is determined by the natural opening angle of the source. The diffraction limited resolution in the vertical plane can be estimated by replacing θ by Ψ_{SR} in equation (5). The difference between using a slit and an iris is illustrated in figure 3 for the SRS.

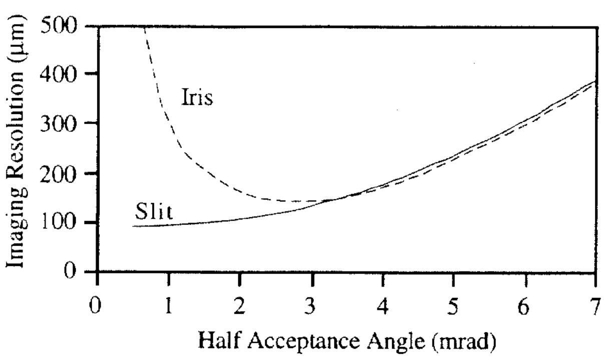

Figure 3. Apparent vertical width of a beam of narrow cross-section vs half acceptance angle for a slit and a circular iris.

Clearly the best vertical resolution is found by using a narrow vertical slit. However, since it is common to measure the profile of both planes with the same detector (eg a CCD camera) this is not always practical. Generally a compromise must be found between the resolution of the two planes in setting the horizontal acceptance, but since the vertical source size is usually much smaller than the horizontal it is normal to sacrifice some horizontal resolution in favour of the vertical. In fact, in modern 3rd generation light sources the vertical beam size may be significantly less than the diffraction limited resolution. In this case accurate profile measurements can best be made with light of a significantly shorter wavelength.

3. Charge Coupled Devices

The most common detector used for measuring beam profiles is the Charge Coupled Device (CCD). Such a device is a solid state detector that essentially consists of an array of discrete potential wells (known as pixels) that store accumulated charge. The charge, induced by incident photons, is read out sequentially. A complete description of CCDs is given in ref [2]. The CCD chip has a well defined geometry, which makes them ideal for metrology, with typical pixel sizes of 20 μm x 20 μm. Each chip will contain something like 512 x 512 pixels.

CCDs can have two geometries, Frame Transfer and Inter-Line Transfer (figure 4). Both of these can be used for profile measurements. The difference between the two types relates to the method used for reading out the accumulated charge. Each CCD has a memory area that is light insensitive to which all of the stored charges are transferred after a fixed integration time. The Frame Transfer type has a better horizontal spatial resolution but the Inter-Line type has a faster image to memory shift [3].

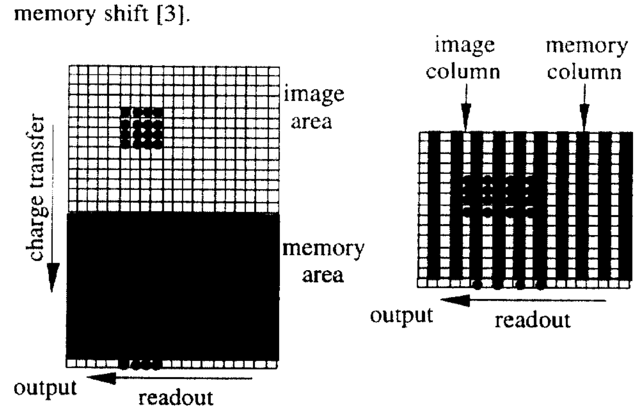

Figure 4. The two types of CCD detector. Frame Transfer on the left and Inter-Line Transfer on the right.

In order to use these devices for profile measurements it is necessary to connect the CCD camera to a framegrabber. A framegrabber is a device that interrogates the CCD and stores the reading for each pixel in buffer memory. It essentially consists of an Analogue to Digital Converter and some RAM (eg for an 8 bit ADC and 512 x 512 pixel array, 256 kbytes are required).

The CCD and framegrabber each have their own internal clocks for controlling timing functions. To achieve the best resolution it is necessary to synchronise these internal clocks [4] although for most applications this would only prevent a small error.

The framegrabber is usually a plug-in computer card. The values in the framegrabber memory can be manipulated by the computer to find the beam profiles. Although the framegrabber generally comes with some commercial software, this is not normally sufficient. It is not uncommon to have to write software for controlling the framegrabber and for determining the beam profiles. This software will have to determine the centre of the beam using some peak detection algorithm, and then select the appropriate pixels for each plane. This is not straightforward and may need to be optimised for each particular application. For example, at Elettra this has been resolved by averaging and smoothing [5].

It is important to remember when using CCD cameras that the output is not necessarily linear with light intensity. It is common for camera manufacturers to apply a so-called 'gamma correction' to the CCD output to compensate for the fact that TV monitors have a non-linear response. Although the optical detector itself is inherently linear, the electronics in most cameras applies a logarithmic scaling to the output. If this correction factor is not removed either by adjusting the camera hardware or software then the CCD will not give accurate beam profile measurements [6].

It is often desirable to measure several beam profiles rapidly, over a few ms say, to investigate beam damping or instability. Unfortunately CCDs are relatively slow, running at TV refresh rate speeds. By screening off ≈90% of the optical detector (Frame Transfer type) and using it as a memory area it has been shown that it is possible to measure a short burst of profiles at around 10 kHz [7].

It is also useful to be able to monitor beam profiles from linacs or synchrotrons at their repetition rates of typically 50Hz. This can best be achieved by using fast shutters locked to the beam cycle. Mechanical shutters are possible but electro-optical ones are preferred. These are a sandwich of a photocathode, micro-channel plate and phosphor screen. The shutter is controlled by gating the accelerating potential across the micro-channel plate. Such a shutter has been used to monitor profiles stroboscopically turn-by-turn in the SLC damping rings [8].

4. PHOTODIODE ARRAYS

An alternative detector that can be used for measuring profiles is the Photodiode Array (PDA) [9]. This is a one dimensional strip of photodiodes (typically 25 μm long) that have an output that is linearly dependent upon the light intensity. This is a purely analogue device, unlike the CCD and framegrabber. The photodiodes are read sequentially and the output can be observed on a scope.

Of course, since the arrays are one dimensional the profile of only one plane can be observed. Therefore two arrays are required to measure both horizontal and vertical profiles simultaneously. This does however have the advantage of allowing the optical system to be optimised for each plane unlike the two dimensional CCD. The other advantage of the one dimensional array is that the need to find the centre of gravity of the beam is removed, greatly simplifying the measurement procedure.

Unlike the CCD the PDA does not lend itself easily to computer control. One method of overcoming this is to control the scope observing the PDA output. This has been successfully demonstrated at Daresbury where the scope is controlled over the GPIB interface [10]. Here, the scope trace is captured by the computer and the profile determined.

Typical integration times for PDAs are ≈25 ms, so like the CCD they are not ideally suited to rapid profile measurements. However the fast shutter that was mentioned in the previous section could equally well be applied to the PDA.

5. CALIBRATION

An important requirement that must not be overlooked is proper calibration of the detector. In many cases the accuracy of the final measurement is limited by calibration error rather than by imaging resolution. Calibration here refers to the determination of the magnification of the optical system employed and so relates the measured profile width in the laboratory to the actual width in the storage ring.

Of course, if the focal lengths of the lenses used is well known then a theoretical calibration can be predicted. However it is always desirable to check this by experiment. This can best be achieved by moving the electron beam by a known amount and measuring how far the focussed image moves. The electron beam can be moved with local bumps or by varying the RF frequency, so long as the change in position of the beam is accurately known.

6. SUMMARY

Measurement of beam profiles with synchrotron radiation is now commonplace. A review has been given of the points that need to be considered when deciding upon a particular technique. The simplest method to use is based upon a photodiode array detector. However, the most common method employed is with a CCD camera and framegrabber. This may take longer to commission because of software requirements but the final product has greater potential.

7. REFERENCES

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