THE BEAM PROFILE MONITORS FOR ELETTRA

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Abstract

The emittance of a synchrotron radiation light source, can be easily deduced from a measurement of the beam profile. For ELETTRA, like for several previous machines, the profile monitor will use a charged coupled device (CCD) sensor mounted on a bending magnet light port. However, considering the small size of the electron beam (100 μm x 60 μm),we need to know the measurement accuracy that can be achieved in the visible. After approximating the image distribution of an hypothetical punctual beam to a gaussian, we define the r.m.s. value of that gaussian as the "punctual beam enlargement". Then we calculate or estimate this quantity for the various contributing errors: diffraction, depth of field and orbit curvature. The analysis is checked at BESSY in Berlin, using part of the actual hardware and software. On ELETTRA, a 41 μm punctual beam enlargement should be achieved in the horizontal plane in the visible and 17 μm in the vertical one, which is satisfactory. In addition, we mention a modification of the CCD acquisition electronics for scanning the evolution of the beam emittance during the acceleration cycle of a 10 Hz booster.

Introduction

A major task of the third generation synchrotron radiation sources like ELETTRA is to deliver high brilliance photon beams to their users. This is achieved by designing a very low emittance machine. The emittance can be easily deduced from a measurement of the beam profile.The principle of this measurement is to focus the beam image on a charged coupled device (CCD), calculate the vertical and horizontal beam sizes and send them in the control room. In this paper, we calculate the measurement errors due to the optics aberrations and show the result of the measurements done at BESSY in Berlin using the actual electronics hardware and software.In addition to the electronics of the CCD camera a special board allows to measure the evolution of the beam size during the acceleration ramp of a 10 Hz booster, initially foreseen as injector. It was tested in the laboratory using a pulsed light source.

Measurement Resolution

The image of a punctual source through any optical system is not a point. Usually the resolution is defined as the minimum distance between two punctual sources which can be resolved by the system. In our case, with a gaussian beam, it is convenient to approximate the image which could be produced by a punctual beam to a gaussian distribution. We will call *punctual beam enlargement* the r.m.s. value of that distribution.

Diffraction and depth of field are the main effects limiting the resolution of the beam profile measurement [1]. The finite length of the photon source in a bending magnet produces a spherical aberration, usually called depth of field error. This error is the same in both planes. On the other hand the diffraction is due to the limited opening angle of the photon beam. This effect is different for each plane: it depends on the vertical aperture in the vertical plane and on the horizontal aperture in the horizontal one.

Considering the vertical plane only, the minimum error due to these effects is obtained without limiting the vertical aperture and by placing a slit as small as possible in the horizontal plane: the minimum diffraction error is given by the natural opening angle of the photon beam; the depth of field error is reduced by limiting the length of the emitting source. We see that a circular diaphragm would increase the diffraction error if its aperture is smaller than the beam natural opening angle, on the contrary a slit limiting only the horizontal aperture does not present this inconvenience.

Considering the horizontal plane, a slit which limits the horizontal aperture reduces the length of the emitting beam and the depth of field error, but it increases the error due to diffraction. Another error is due to the curvature of the electron beam in the bending magnet which increases with the aperture of the slit. There is an optimum value to the slit aperture which minimizes the combination of those effects.

The *punctual beam enlargement* ε_{DF} due to the depth of field effect [2,3] can be computed considering the radius of the circle of least confusion ε (Figure1,2). It is defined by:

$$\varepsilon = \frac{L}{2}\theta_H = R\,\theta_H^2 \qquad (1)$$

with L length of the emitting source, θ_H half opening angle and R radius of curvature of the particle trajectory.

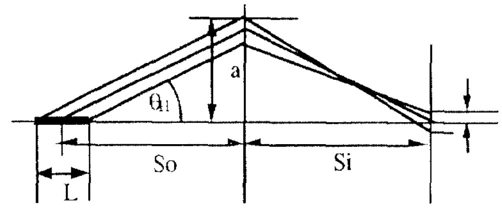

Figure1. The image of a punctual beam is not a point.

The intensity distribution of the image can be approximated to a gaussian whose r.m.s. value is:

$$\varepsilon_{DF} = K_{DF}\,R\,\theta_H^2 \qquad (2)$$

with $K_{DF} = 0.5$.

The *punctual beam enlargement* due to diffraction from a slit at a given wavelength λ can be calculated approximating the diffraction pattern to a gaussian distribution whose r.m.s. value is:

$$\varepsilon_{Diff} = K_{Diff}\frac{\lambda}{\theta} \qquad (3)$$

with θ half opening angle.

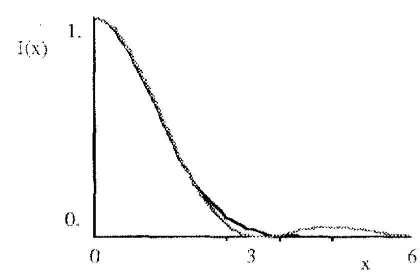

Figure 2.Approximation of the diffraction pattern with a gaussian distribution.

We obtained the best approximation using the least squares fit method and the coefficient computed is

$$K_{Diff} = 0.1830 \qquad (4)$$

The curvature of the particle trajectory produces an error only in the horizontal plane[4]:

$$\varepsilon = \frac{1}{2}R\,\theta_H^2 \qquad (5)$$

approximating it with a gaussian distribution, the *punctual beam enlargement* due to this effect is:

$$\varepsilon_C = K_C\,R\,\theta^2 \qquad (6)$$

with $K_C = 0.5$.

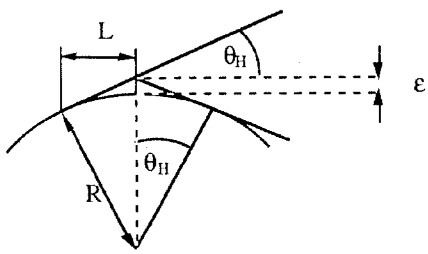

Figure 3. Error due to the curvature of the particle trajectory.

Using a slit which limits only the horizontal aperture, the *punctual beam enlargement* due to the diffraction in the vertical plane at a given wavelength is:

$$\varepsilon_{Diff\text{-}V} = 0.1830 \frac{\lambda}{\theta_N} \tag{7}$$

and in the horizontal plane:

$$\varepsilon_{Diff\text{-}H} = 0.1830 \frac{\lambda}{\theta_H} \tag{8}$$

The *punctual beam enlargment* due to depth of field in both horizontal and vertical plane is:

$$\varepsilon_{DF} = 0.5\ R\ \theta_H^2 \tag{9}$$

The *punctual beam enlargement* due to the curvature of the trajectory in the horizontal plane is

$$\varepsilon_C = 0.5\ R\ \theta_H^2 \tag{10}$$

The total *punctual beam enlargement* in the vertical plane is easily calculated:

$$\varepsilon_V = \sqrt{(\varepsilon_{DF})^2 + (\varepsilon_{Diff\text{-}V})^2} \tag{11}$$

while in the horizontal plane is:

$$\varepsilon_H = \sqrt{(\varepsilon_{DF})^2 + (\varepsilon_{Diff\text{-}H})^2 + (\varepsilon_C)^2} \tag{12}$$

If the source is not a punctual beam but is a gaussian one, with vertical and horizontal r.m.s. dimensions respectively σ_{BV} and σ_{BH}, the intensity distribution of the image is also a gaussian whose vertical sigma is:

$$\sigma_V = \sqrt{(\sigma_{BV})^2 + (\varepsilon_V)^2} \tag{13}$$

and the horizontal one is

$$\sigma_H = \sqrt{(\sigma_{BH})^2 + (\varepsilon_H)^2} \tag{14}$$

The ELETTRA bending magnet radius is 5.5 m. The half natural opening angle of the beam is 2.7 mrad. We use a bidimensional array of CCDs for detecting the photon beam; they work in the visible. We place a slit limiting the horizontal aperture and a bandpass filter centered at 450 nm before the CCD. The optimum aperture of the slit which minimizes the errors in the horizontal plane is:

$$\theta = 2.5 \text{ mrad} \tag{15}$$

at this horizontal opening angle the total *punctual beam enlargement* in the horizontal and in the vertical plane are:

$$\varepsilon_H = 41\ \mu m; \qquad \varepsilon_V = 17\ \mu m \tag{16}$$

the beam size at the bending magnet port with a 1.5 GeV beam and a 10% coupling value is

$$\sigma_{BH} = 100\ \mu m; \qquad \sigma_{BV} = 60\ \mu m \tag{17}$$

and the beam dimensions measured are:

$$\sigma_H = \sqrt{100^2 + 41^2} = 108\ \mu m \tag{18}$$

$$\sigma_V = \sqrt{60^2 + 17^2} = 62\ \mu m \tag{19}$$

that represents an error smaller than 8% in the horizontal plane and than 4% in the vertical plane.

System Description

The synchrotron radiation light comes out of the 3.5° port of a bending magnet [5]. The first mirror, in vacuum, is placed at the Brewster angle with respect to the horizontal plane [6] in order to eliminate the vertically polarized light: it should sligthly improve the resolution. The mirror absorbs the most energetic part of the photon beam and reflects all the radiation at wavelengths longer than 180 nm. A slit limits the horizontal aperture to 2.5 mrad. A bandpass filter is centered at 450 nm. A fused silica quartz lens, that covers the visible and UV range, converts the radiation cone in a parallel beam. A battery of attenuation filters extends the dynamic range by avoiding the saturation of the sensor. Several lenses with different magnifications focalize the beam on the CCD.

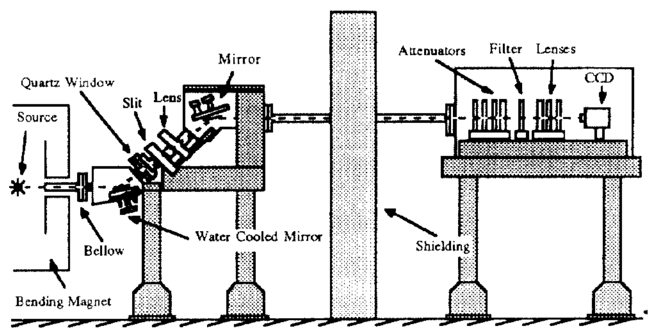

Figure 4. Measurement setup.

The CCD (Thomson model TH7863) is a bidimensional array of 288 x 384 square cells of 23 µm each [7]. Its functional wavelength extends from 1000 nm down to 400 nm.

An Image Processing Board [8] digitizes the picture of the beam and stores it in a memory that can be read from the VMEbus [9].

The system is working using OS-9 operative system [10] and a program which finds the beam center and the horizontal and vertical sizes has been developed. The results of the calculation can be sent to the control room through the network [11].

In addition to that electronics we developed a special board [12] for the profile monitor of a 10 Hz booster synchrotron, initially foreseen as ELETTRA injector. It has been tested with a simple simulation of the light source ramped in intensity. The image, after being sampled in 2 ms, is processed fast enough for yielding the beam dimensions at a 10 Hz rate. In addition, by delaying slightly the sampling time from one period to the next, the curve showing the evolution of the beam profile during the acceleration cycle can be available every 2.5 seconds.

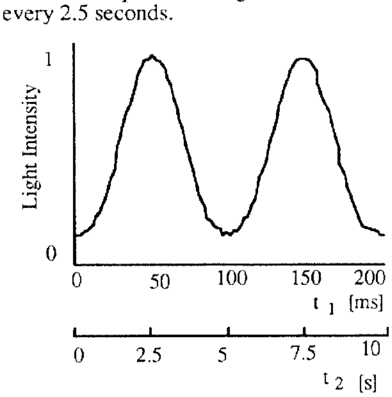

Figure 5. The evolution of the beam intensity at the time t_1 is detected at the time t_2: a 10 Hz period is available after 5 seconds.

A Test at BESSY

The system has been tested at BESSY, in Berlin (Germany), using the light coming from a bending magnet. The goals are to test electronics and software and confirm the theoretical predictions about the resolution.

The optics magnification factor is 4.2. A set of attenuators avoids saturating the sensors. A horizontal plane limiting slit, a vertical plane limiting slit and a circular diaphragm are successively placed just behind the window. The half aperture range extends from 0.5 to 20 mm, the distance between the source and the window being 3.29 m, the half aperture angle extends from 0.1 to 6 mrad. The sextupoles are switched off for reducing the vertical beam size down to about 30 µm and measuring the various *punctual beam enlargements*. Two bandpass filters centered at 450 nm and 550 nm are successively introduced. A program finds the beam center and calculates the beam size at different optics setups.

The analysis of the images first done at BESSY with the OS9 system, has been completed later on in Trieste with a graphics workstation.

The noise has been the main problem for finding the beam center: there is not only one maximum intensity point. That problem has been reduced by averaging several acquisitions and by smoothing the final image.

The irregular background intensity has been the main problem for calculating the r.m.s. values of the beam intensity distribution. It has been solved working with the gradient transformed image: the maximum intensity points of that image correspond to the r.m.s.values of the original one.

A 16° tilt of the beam with respect to the horizontal plane limits the separation between horizontal and vertical enlargement: an enlargement which occurs in the horizontal plane modifies not only the horizontal size of the beam, but the vertical one too.

No change in the vertical beam size has been observed when the horizontal opening angle has been varied from 0.1 to 6 mrad. The reason is that the maximum vertical enlargement due to the depth of field error corresponds to only 12 µm (only 2 pixels on the CCD) if the vertical beam size is 30 µm.

Conclusions

The analysis of the images taken at BESSY using the electronic part of the system confirms the theoretical predictions: the enlargement due to diffraction depends on the vertical aperture in the vertical plane and on the horizontal aperture in the horizontal one. The best resolution in the vertical plane is obtained by reducing the horizontal opening as much as possible. Any limitation of the vertical opening angle would deteriorate the vertical resolution.

The accuracy of the measurement in the visible (450 nm) is sufficient with these beam dimensions: 100 µm horizontal and 60 µm vertical. However the vertical size calculated with a 10% coupling value might be pessimistic. If the coupling value is reduced down to one percent, the beam height becomes of the same order of magnitude as the *punctual beam enlargement*. In that case we may have to work in the UV to reduce that error.

Acknowledgements

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References

[1] A. Hofmann, F. Meot, Optical resolution of beam cross-section measurements by means of synchrotron radiation, NIM 203 (1982) pp. 483-493.

[2] M. V. Klein, T. E. Furtak, Optics, John Wiley & Sons (1986).

[3] M. Born, E. Wolf, Principles of optics, Pergamon Press (1989).

[4] A. P. Sabersky, The geometry and optics of synchrotron radiation, SLAC-PUB-1245 (A) May 1973.

[5] G. R. Aiello, Emittance Measurement Project , Sincrotrone Trieste Report, ST/M-88/29, December 1988.

[6] G.R.Aiello, Power Density for the Beam Profile Measurement in the Sincrotrone Trieste, Sincrotrone Trieste Internal Report, ST/M-TN-89/4, January 1989.

[7] Thomson Electronics, The CCD Image Sensors manual, (1988).

[8] Themis, TSVME631 Image Acquisition User's manual, (1988).

[9] VMEbus Specifications, IEEE 1014-87 or IEC 821.

[10] Microware System Corp., OS-9 Operative System Technical Manual.

[11] P.Michelini, The ELETTRA controls and Acquisition, Presented to this Conference.

[12] G. R. Aiello, F. Cavazzoni, Acquisition System for the ELETTRA Beam Profile Monitor, Sincrotrone Trieste Report, ST/M-89/24, December 1989.