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DESIGN STUDY ON BEAM SIZE MEASUREMENT SYSTEM USING SR INTERFEROMETRY FOR LOW BEAM CURRENT*

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Abstract

To enable reliable measurements of the small vertical size of the electron beam in the Duke storage ring, a measurement system is being developed using synchrotron radiation interferometry (SRI). By relating the transverse beam size to the transverse spatial coherence of synchrotron radiation from a dipole magnet according to the Van Cittert-Zernike theorem, the transverse beam size can be inferred by recording and fitting the interference fringe as a function of the characteristic features of the interference filter used. In this paper, we describe the preliminary design of such a measurement system and present design considerations to make it possible to measure the electron beam vertical size for a wide range of electron beam energies and currents.

Especially this system will be optimized to measure the electron beam size for low current operation down to 50 to 100 µA. This beam size measurement system will be used as an important beam diagnostic for the intrabeam scattering research at the Duke storage ring.

INTRODUCTION

The measurement of the transverse beam size, therefore, the transverse emittance, is one of the most important diagnostics for a storage ring-based light source. Several different types of transverse beam size measurement methods were developed in the past few decades using non-invasive or quasi-non-invasive techniques [1]. Among them, synchrotron radiation (SR) is commonly used due to its non-invasive nature.

To achieve a high resolution for small transverse size electron beams, the synchrotron radiation interferometry (SRI) method was introduced [2]. By relating the transverse beam size to the transverse spatial coherence of synchrotron radiation from a dipole magnet according to the Van Cittert-Zernike theorem, the transverse beam size can be inferred by recording and fitting the interference fringe using the characteristic features of the interference filter used. This method was later developed to simultaneously measure both the horizontal and vertical beam sizes by implementing a diffracting mask with 4-circular apertures [3].

The Duke storage ring (DSR) is a dedicated electron-beam driver for the Duke Free-Electron Laser (FEL) and the High-Intensity Gamma-ray Source (HIGS). The electron beam energy in the storage ring can be varied from 240 MeV to 1.2 GeV to generate a high-intensity gamma beam in a wide range of energies for scientific research [4]. The transverse beam size measurement system at the DSR was developed using the SR imaging method, and it was carefully calibrated and optimized to achieve a high resolution of about 30 µm [5]. While adequate to measure the horizontal beam size, it was not capable of measuring the small vertical beam size. Therefore, a higher resolution system to measure the vertical beam size needs to be developed and the SRI technique is chosen for this system.

In this paper, the consideration and design of the SRI vertical beam size measurement system are described, optimizations for low-current beam measurements are discussed, and error-related effects are presented. This system will be capable of measuring the electron beam size in a wide range of electron beam energies and currents. It will be used as one of the critical diagnostics for the intrabeam scattering (IBS) research at the Duke storage ring.

CONSIDERATIONS AND DESIGN

Unlike typical synchrotron radiation light sources, the DSR is operated using electron beams of a range of energies and currents to produce Compton gamma-ray beams of different energies and energy spreads (with collimation). This leads to a large variation of the electron beam size for different Compton beam production runs. The zero current beam sizes at different energies are shown in Table 1,in which the beam sizes are increased by a factor of about five with the increase of the beam energy. When taking the IBS effects into account, the overall factor for the beam size changes will be larger. Furthermore, to measure the electron beam size at a low current, the low photon flux issue should be considered.

Table 1: The Zero-current Electron Beam Size at Different Energies in the DSR for 3% Emittance Coupling

E_e [MeV]	250	480	1000	1200
σ_x [µm]	39.7	76.4	159.0	191.0
σ_y [µm]	13.2	25.4	52.9	63.5

Synchrotron Radiation Interference Method

It is well known that a spatially coherent light produces an interference pattern after passing through a double slit. Let us consider an interference mask with either two rectangular slits or round holes vertically separated by a distance D_y with the slit opening or hole diameter d. When the synchrotron radiation from an electron beam passes through this aperture, the intensity distribution of the interference pattern at a distance can be described by:

$$I(y) = A^2 \int [f(R)]^2 \{1 + \cos[B]\} \rho(y_e) dy_e \qquad (1)$$

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where $f(R) = \frac{\sin(R)}{2R}$ for the rectangular slit and $f(R) = \frac{J_1(R)}{R}$ for the round hole, $A = \frac{\pi A_0 d^2}{2\lambda L_s L_0}$, $R = \frac{\pi d}{\lambda}\left(\frac{y_e}{L_0} + \frac{y}{L_s}\right)$, $B = \frac{2\pi D_y}{\lambda}(\frac{y_e}{L_0} + \frac{y}{L_s})$, A_0 is the amplitude of the radiation field, λ is the wavelength, L_0 is the distance from the electron beam to the mask, L_s is the distance from the mask to the imaging plane, y_e is the vertical position of the electron beam, $\rho(y_e)$ is the vertical intensity distribution of the electron beam.

Assuming that the electron beam has a Gaussian transverse distribution, and keeping the zero-order term of $[f(R)]^2$ in the integration, the analytical expression for the interference pattern can be found. The simplified expression to fit the interferometry fringe for rectangular slit is given by

$$f_1(y) = a\,\mathrm{sinc}^2(by + c)[1 + \exp(-d)\cos(ey + f)] + h, \quad (2)$$

and for round holes, it is

$$f_2(y) = a\left[\frac{J_1(by + c)}{by + c}\right]^2 [1 + \exp(-d)\cos(ey + f)] + h, \quad (3)$$

where the parameters a to h are determined from fitting, and $\gamma = \exp(-d)$ is known as the visibility. The vertical beam size σ_y can then be expressed using the fitted parameter d:

$$\sigma_y = \frac{\lambda L_0}{\pi D_y}\sqrt{\frac{d}{2}}. \quad (4)$$

For round holes, we can keep one extra term by expanding $[f(R)]^2$ in Eq. (1) to the first order, and the function to fit the interference fringe is

$$\begin{aligned} f_3(y) =& a\left(\frac{J_1(by + c)}{by + c}\right)^2 [1 + \exp(-d)\cos(ey + f) \\ &+ gd\frac{J_2(by + c)}{J_1(by + c)}\exp(-d)\sin(ey + f)] + h. \end{aligned} \quad (5)$$

The interference image captured by the camera is simulated using Synchrotron Radiation Workshop (SRW). An example of the simulation intensity profile is shown in the left plot of Fig. 1, a vertical cut of the image and its fits using f_1, f_2, and f_3 are shown in the right plot.

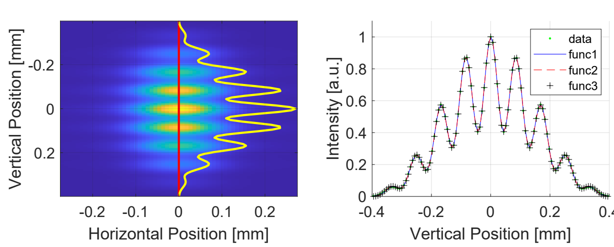

Figure 1: Left: Simulated interference image at the location of the camera using SRW. Right: The normalized intensity distribution (stars) along the vertical center, the lines and crosses are fittings using f_1, f_2, and f_3 defined in the text.

Large Aperture Opening

While testing an SRI system on the DSR using a slit with a small opening, the measured photon intensity was found to be too low for a beam current below 100 µA. The camera exposure time would have to be increased to tens of seconds to obtain an image with reasonable intensity. A long exposure was not desirable as the image quality suffered due to electron beam motion and vibrations of the measurement system. A better way to increase the image intensity is to enlarge the slit or hole openings. The influence of slit or hole openings on the measured beam size is studied using SRW simulations. In the simulation rectangular slits are used, and the interference fringes are simulated by varying the slit opening while keeping the slit separation and other parameters unchanged. The interference fringes are simulated and fitted using aforementioned three functions.The corresponding beam sizes are calculated using Eq. (4) and the results are shown as solid lines in Fig. 2. It is observed that the beam size shifts downward with larger slit openings.

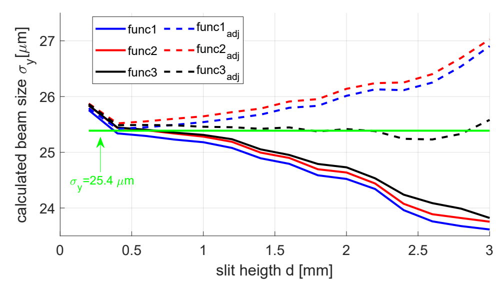

Figure 2: Calculated beam size as a function of the slit opening. The solid lines show the results calculated with the preset aperture separation D_y; the dash lines are calculated with the effective separation D_y^{eff}, different color presents fitting with different functions. The ideal beam size is 25.4 µm (green-line), and the slit separation is 7 mm.

An adjustment is made to set an effective slit opening D_y^{eff} using the fitted parameter e_{fit}

$$D_y^{eff} = e_{fit}\frac{\lambda L_s}{2\pi} \quad (6)$$

and then the effective slit separation is used in Eq. (4) to calculate the beam size. The beam sizes calculated using the effective separations are shown as dash lines in Fig. 2. It is found that the calculated electron beam size using the effective slit separation and the expanded expression of Eq. (5) yields more consistent results with the input beam size $\sigma_{y,0}$ for a range of values of the slit opening.

Intensity Imbalance

So far the distributions of photon intensity at two slits are assumed identical. However, in practice, there is always some difference in the intensity distributions at the two slits due to various errors in alignment, slit fabrication, etc. Let I_1 and I_2 be the intensities at two slits respectively and assume that $I_1 > I_2$. The intensity imbalance δ_{II} and its influence

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on the measured visibility F_{II} can be written as

$$\delta_{II} = \frac{I_1 - I_2}{I_1 + I_2}, \quad F_{II}(\delta_{II}) = \frac{\gamma_{II}}{\gamma_0} = \sqrt{1 - \delta_{II}^2} \tag{7}$$

where γ_0 is the expected visibility and γ_{II} is the visibility with intensity imbalance.

The relation between F_{II} and δ_{II} is shown in the left plot of Fig. 3. The relative visibility change due to this effect is not very significant with a small δ_{II}. For example, $F(0.142) = 0.99$, which means when the photon intensity imbalance at two slits is 14.2%, the visibility will be reduced by only 1%. However, this is a systematic error in the system, and it affects the measured beam size differently at different size beams or visibilities, as shown in the right plot of Fig. 3. The relative beam size error increases dramatically when the measured visibility value is close to unity. This suggests the measurements to be designed with a reasonably smaller visibility when a significant intensity imbalance is expected.

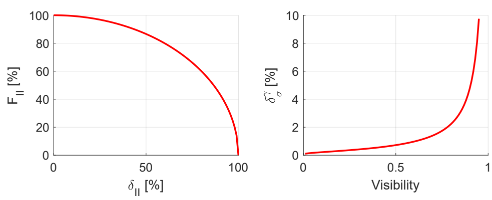

Figure 3: Left: Influence of the intensity imbalance on the measurement visibility. Right: The relative beam size error as a function of visibility for a case with a constant -1% relative visibility error in the system.

Detector Sensitivity

Let the intensity resolution of the camera sensor be ΔI and the average intensity of the measurement $I_{avg} = (I_{max} + I_{min})/2$, where I_{max} and I_{min} are the intensities at the peak and valley of the interference pattern [6]. Then, the measured beam size error can be related to the sensor sensitivity by

$$\delta_\sigma = -\frac{\Delta I / I_{avg}}{2\gamma \ln \gamma} \tag{8}$$

The measured beam size error with different visibilities are calculated and shown in Fig. 4, where the detector sensitivity is assumed to be $\Delta I / I_{avg} \sim 0.4\%$. It is observed that the relative beam size error increases at the extremes of visibility, while it is almost insensitive in the range of 0.1 to 0.8. The minimal relative beam size error is found to be around 0.4, which is the optimum visibility value for a measurement.

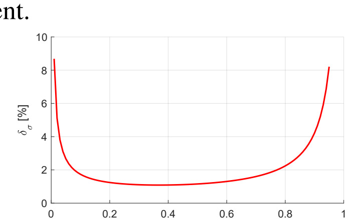

Figure 4: Beam size measurement error as a function of visibility for a given detector sensitivity.

Layout and Parameters

Due to the space limitation, our SRI system for vertical beam size measurements is designed to be installed on the same optical table which also hosts the current horizontal beam size measurement system. As shown in Fig. 5, a mirror (#1) is installed to reflect part of the dipole synchrotron radiation to the new system. A focusing lens ($f = 1$ m) located $L_0 = 2$ m away from the electron beam is used to focus the beam on to a two-slit plate with a slit separation $D_y = 5$ mm. The polarizer and the band-pass filter are used to make polarized and monochromatic beams, respectively.

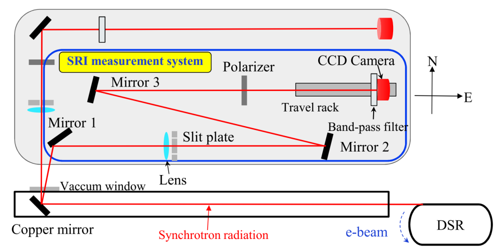

Figure 5: Layout of the SRI measurement system at DSR.

Table 2: Expected Visibility for Different Size of Beam

D_y [mm]	d_y [mm]	λ [nm]	σ [μm]	Visibility γ
5	2	330	13.2	0.821
			25.4	0.482
			45.0	0.101
		700	25.4	0.850
			63.5	0.362
			95.0	0.103

Two band-pass filters will be used one at a time to enable the measurements of the electron beam with a wide range of beam sizes while keeping the measured visibility in a reasonable range, see Table 2. This system is also designed to be capable of measuring the small horizontal beam size in the low energy range. This will enable us to cross-check and calibrate the new system with the existing beam profile measurement system using the direct imaging technique.

SUMMARY AND DISCUSSION

A high-resolution beam size measurement system using synchrotron radiation interference has been designed for the Duke storage ring. The effect of a large slit opening on the beam size has been studied, and a compensation method is proposed to provide more consistent beam size results for a range of slit openings. A large slit opening allows this system to measure the vertical beam size of low-current beams. The influence of the intensity imbalance between two slits on the beam size is discussed, as well as the effect of the detector sensitivity. This system is designed to measure the vertical beam size for a wide range of electron beam energies and currents. It will be used as an important beam diagnostic system for the intrabeam scattering research at the Duke storage ring.

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