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SIMULATION OF A QUAD-SLITS INTERFEROMETER FOR MEASURING THE TRANSVERSE BEAM SIZE IN HLS-II*

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Abstract

A quad-slits interferometer using visible light is designed to measure the transverse beam size of Hefei Light Source-II (HLS-II). According to the basic beam parameters of the B7 source point, the preliminary simulation results are obtained by using the Synchrotron Radiation Workshop (SRW) code. Furthermore, the core parameters of the quad-slits components in the interferometer are optimized. Among, the optimum slits-separations of d_H and d_V are acquired to be 6.0 and 10.0 mm, respectively. It is shown that the simulated results are consistent with the theoretical values, which provides a reference value for performing the related experimental measurement in the future.

INTRODUCTION

It is known that the synchrotron radiation (SR) refers to the electromagnetic wave radiated when the acceleration state of the charged particles changes. So far the SR light source has been widely used in the fields of condensed-matter physics, medical research, biochemistry, materials and advanced manufacturing processes due to its significant characteristics of high-brightness, high polarization and good stability. With the advancement of accelerator science and technology, the transverse beam size becomes smaller and smaller and reaches few dozens of micrometers. There is no doubt that it requires a huge engineering challenge to accurately measure such a small beam size. The current mainstream technology for the measurement of the transverse beam size is to employ the SR optical system. It is especially pointed out that this SR system has the excellent advantage of real-time and online measurement without damage to the stored bunched beam [1]. Up to now, the traditional methods for measuring the transverse beam size include FZP imaging [2], double-slits and quad-slits interferometry [3,4], pinhole imaging [5] and so on [6,7]. Among them, the FZP imaging method is considered as uneconomical because of the smaller beamline layout in HLS-II and the expensive optical diffractive element FZP. As for the pinhole imaging method, it is difficult to measure the small transverse beam size owning to the inevitable optical diffraction effect. In addition to the double-slits interferometer proposed by T. Mitsuhashi [8], which possesses high resolution that can be used in visible light and even X-ray bands. In combination with the remarkable merits of the optical interference measurement system, the B7 beamline of HLS-II has been achieved the online measurement of the transverse beam size. This previous double-slit interferometry occupies a large space and has a high maintenance cost. In order to further precisely obtain the beam size of B7 source point, we are devoted to designing a simple suitable quad-slits interferometer which can reduce the complexity of the optical system.

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PRINCIPLE AND PHYSICAL DESIGN

HLS-II is a second-generation electron storage ring with low emittance of 36.4 nm·rad and with beam energy of 800 MeV. Note that a double-slits interferometer already has been applied to measure the transverse beam size of B7 source point. Then we are desired to design a new quad-slits interferometer for improving the measurement accuracy and system robustness. The parameters of B7 source point are clearly shown in Table 1.

Table 1: The Parameters of B7 Source Point

Parameters	**Value**
Electron beam energy E_e (GeV)	0.8
Beam current I (mA)	400
Circumference L (m)	66.1308
Radius of BM ρ (m)	2.1645
Vertical magnetic field of BM B (T)	1.2327
Transverse natural emittance ϵ (nm·rad)	36.4
Energy spread (RMS)	0.000 47
β_x (m)	1.7668
β_y (m)	12.3485
α_x (m)	−3.002
α_y (m)	2.1319
η_x (m)	0.1059
η_x'	−0.1990

According to the above parameters given in Table 1, the transverse beam size can be calculated by

$$\begin{cases} \sigma_x^2 = \varepsilon_x\beta_x + (\eta_x\frac{\Delta p}{p})^2 \\ \sigma_y^2 = \varepsilon_y\beta_y \end{cases} \tag{1}$$

where σ_x and σ_y are the horizontal and vertical beam size, respectively. ε_x and ε_y are the horizontal and vertical beam emittance, respectively. β_x and β_y are the horizontal and vertical beta function, respectively. Δp/p is the energy spread and η_x is dispersion function. Through the calculation we

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can know that the theoretical horizontal and vertical beam size of HLS-II are 255.98 and 93.88 µm, respectively. In terms of the Van Cittert-Zernike theorem, the coherence of two points in space can be expressed by the Fourier transform of the light source with a standard Gaussian distribution. The structure of the quad-slits interferometer designed using this principle is distinctly shown in Fig. 1.

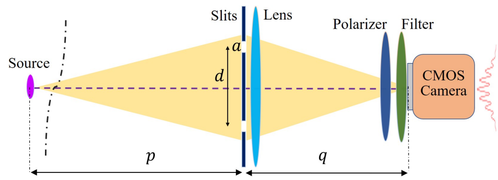

Figure 1: The particle trajectories under different RF phase modulation amplitudes (f_s=21.3 kHz and f_m=20.0 kHz).

In Fig. 1, p is the distance from the light source to the quad-slits component, and q is the distance from the quad-slits component to the CMOS camera. Here, the achromatic lens is used to modulate the wavefront of the light passing through the quad-slits component shown in Fig. 2. to stabilize the interference pattern on the CMOS camera surface. And the polarizer is utilized for obtaining the horizontal polarization light, and the filter is applied to obtain quasi-monochromatic light. It is necessary to use a monochromator instead of a filter to obtain quasi-monochromatic light when using shorter-wavelength light to measure the transverse beam size of the storage ring light source. In fact, we chose visible light of 500 nm as the detection source, which is mainly attributed to the high availability and the large coherence length of this wavelength band. In addition, it is easy to setup and adjust the optical path, which is more convenient for carrying out experiments.

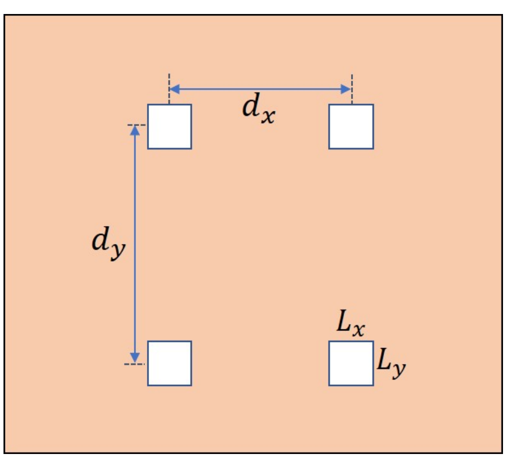

Figure 2: Schematic diagram of the experimental measurement system.

For the extended light source, the horizontal and vertical interference pattern with wavelength λ can be described by the formula [9,10]

$$\begin{cases} I_H(x) = 2I_0L_x^2L_y^2sinc^2(\frac{\pi ax}{\lambda f})(1+\gamma_H cos[\frac{2\pi d_x x}{\lambda f}]) \\ I_V(y) = 2I_0L_x^2L_y^2sinc^2(\frac{\pi ay}{\lambda f})(1+\gamma_V cos[\frac{2\pi d_y y}{\lambda f}]) \end{cases} \tag{2}$$

Here, I_H and I_V denote the horizontal and vertical intensity distribution, x and y denotes the horizontal and vertical coordinate, f denotes the focal length, L_x denotes the slit width, L_y denotes the slit height, d_x and d_y denote the horizontal and vertical slits-separation, respectively. γ_H and γ_V are the horizontal and vertical visibility of the quad-slits interference pattern, which can be expressed as

$$\gamma = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{3}$$

In Eq. (3), I_max and I_min stand for the minimum and maximum intensity of the interferogram near the central position, respectively. In the quad-slits interferometer, the coherence of the quad-slits is equivalent to the visibility of the interference pattern on the CMOS camera. Assuming that the light source is spatially Gaussian distribution, yields

$$\gamma = exp(-\frac{2\pi^2 d^2\sigma^2}{\lambda^2 p^2}) \tag{4}$$

As a consequence, the beam size can be extracted from the measurement of γ, which can be expressed as

$$\sigma = \frac{\lambda q}{\pi d}\sqrt{\frac{1}{2}ln(\frac{1}{V})} \tag{5}$$

In order to measure more accurately in the actual measurement process, the visibility needs to be obtained by fitting the experimental data, rather than through a single point measurement. The fitting equation is described as follows

$$I(x) = a_0 + a_1 sinc^2(a_2 x + a_3[1 + a_4 cos(a_5 x + a_6)]) \tag{6}$$

Here, a_4 indicates the visibility of the interference pattern.

SIMULATION RESULTS

Compared with the previous double-slits interferometry, the newly designed quad-slits interferometry uses a higher resolution CMOS camera (2.5 µm×2.5 µm), and at the same time removes the zoom structure before the CMOS camera. Therefore, this quad-slits interferometry has a simpler optical path and eliminates various aberrations caused by the zoom structure. In the entire optical interference system we designed, the relevant parameters are as follows: p is 12.000 m, q is 1.091 m, the focal length f of the lens is 1.000 m, L_x is 2.0 mm, L_y is 2.0 mm, d_x is 6.0 mm, and d_y is 10.0 mm. According to the above designed parameters, the simulated result of the interference system using SRW code is shown in Fig. 3. By fitting the data of the horizontal and vertical interferogram as shown in Figs. 4 and 5 by Eq. (6), the corresponding visibilities are acquired to be 0.2915 and 0.6743, respectively. It is concluded that the horizontal beam size is 249.90 µm, and the vertical beam size is 84.78 µm. In general, the design of B7 quad-slits interferometry meets the current practical requirements.

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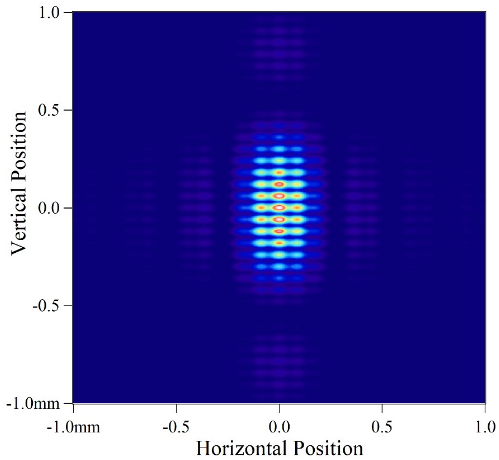

Figure 3: Simulated interferogram of the quad-slits interferometer.

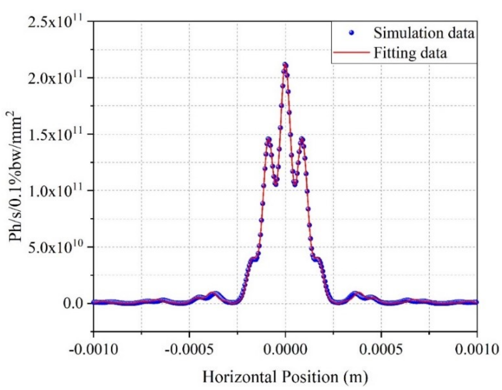

Figure 4: Data fitting in the middle of the horizontal interferogram.

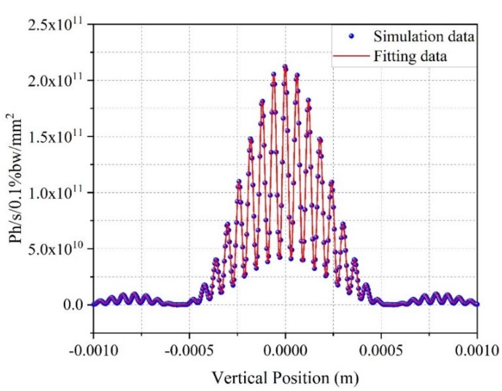

Figure 5: Data fitting in the middle of the vertical interferogram.

CONCLUSION

In this paper, a quad-slits interferometer using visible light was proposed according to the characteristics of the light source. And then, the SRW code is used to obtain the intensity distribution of B7 source point based on the relevant machine parameters of HLS-II. The simulation results of the horizontal and vertical size are obtained as 249.90 and 84.78 µm, respectively. This is of guiding significance to the subsequent optimization and improvement of the experimental measurement system performance. In the next research work, we will further verify the reliability and applicability of the designed interference measurement system.

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