Design of an interference system for measuring the transverse beam size in HLS-II

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ABSTRACT
In this paper, a horizontal and vertical double-slits interferometer using visible light are designed to measure the transverse beam size of Hefei Light Source II (HLS-II). For the given initial structural parameters of the two interferometers, a series of numerical simulations and analyses are carried out by using the Synchrotron Radiation Workshop (SRW) code. Furthermore, the core parameters of the double-slits components in the interferometers are optimized. In the end, the visibilities of the horizontal and vertical interferometer we designed are 0.345 and 0.548 respectively, which are in the range of 0.2–0.6. And simulation results meet the requirement of theoretical relative measurement error of less than 10%.

KEYWORDS
Transverse beam size; synchrotron radiation; interferometer; double-slits

1. Introduction
Synchrotron Radiation (SR) refers to the electromagnetic wave radiated when the acceleration state of charged particles changes. The electron beam in a storage ring can radiate a wide spectrum light when traveling through the Bending Magnet (BM). 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 excellent characteristics of high brightness, high polarization and high stability.

In the storage ring light source, the transverse beam emittance is one of the important parameters to evaluate the machine performance. With the advancement of accelerator science and technology, it is required that the beam emittance becomes smaller and smaller and reaches the order of pm-rad. There is no doubt that it is a huge engineering challenge to accurately measure such a small beam emittance. Generally, the beam emittance can be obtained by measuring the transverse beam size and combining with the Twiss parameters of the machine. Therefore, precision measurement of the transverse beam size is of great significance to measuring the beam emittance of HLS-II.\[1\] The current mainstream technology is to use SR optical system to obtain the transverse beam size. Notably, the advantage of this SR measurement system is that of realizing the real-time and online measurement of the transverse beam size without damage to the stored beam.\[2\]

At present, the methods that use this mainstream technology for measuring the transverse beam size include FZP imaging,\[3,4\] double-slits interferometry,\[5,6\] pinhole imaging\[7,8\] and so on. Among them, the FZP imaging method is not economical in HLS-II due to the smaller
beamline layout and the expensive optical diffractive component FZP. As for the pinhole imaging method, it is especially pointed out that it is difficult to measure the small transverse beam size due to the optical diffraction effect. In addition to the double-slits interferometer proposed by T. Mitsuhashi,[9,10] possesses high resolution that can be used in visible light and even X-ray bands. Owning the remarkable merits of the optical interference measurement system, the B7 beamline of HLS-II has achieved online measurement of the transverse beam size. In order to jointly obtain the beam emittance and energy spread by measuring the transverse beam size of B7 and B8 source points, we are devoted to designing a suitable interference measurement system that can accurately measure the transverse beam size of B8 source point.

2. Principle and physical design

HLS-II is a second-generation electron storage ring with low emittance of 36.40 nm·rad and with beam energy of 0.80 GeV. It is emphasized that there are two diagnostic beamlines B7 and B8 on HLS-II. Note that B7 already has an optical interference measurement system that has been applied to measuring the transverse beam size of B7 source point. Then we are desired to design a new interference system for measuring the transverse beam size of B8 source point and the relative error of the measurement system is required to be less than 10%. The parameters of B8 source point are clearly shown in Table 1.

According to the above parameters given in Table 1, the SR spectral distribution of HLS-II is achieved by means of Synchrotron Radiation Workshop code,[11] as shown in Figure 1. The SRW code was originally developed by European Synchrotron Radiation Facility (ESRF) to use the retardation potential to calculate the electron beam to generate synchrotron radiation. At present, SRW code has been widely used in various synchrotron radiation light sources in the world to simulate and calculate the generation and propagation of synchrotron radiation. It is observed that the SR of HLS-II has outstanding characteristics of high brightness and wide-range spectrum. And the theoretical horizontal and vertical dimensions can be calculated[2] to be 221.90 and 115.29 μm, respectively.

Furthermore, the critical wavelength of the SR can be calculated by

$$\lambda_c = 1.863/(E_e^2 B),$$

where $\lambda_c$ (nm) is the critical wavelength, $E_e$ (GeV) is the Electron energy, and $B$ ($T$) is vertical magnetic field of BM. Throughout the calculation we can know that the critical wavelength of HLS-II is about 2.36 nm. In fact, we chose visible light of 500 nm as the detection light, mainly due to the high availability and the large coherence length of this band. The calculation results using SRW code show that the number of photons with a optical wavelength of 500 nm is $1.57628 \times 10^9$ Ph/s/0.1%bw/mm², which is satisfied with the operating conditions of the optical system. For example, it is easy to obtain optical lenses and CMOS cameras, and the experimental platform can be built outside the vacuum. In other words, it is easy to carry out experiments in this wavelength band. Similarly, the SRW code is used to obtain the distribution of 500 nm SR light, as shown in Figure 2.
It is important to note that the distribution in the horizontal direction is evenly distributed, and the distribution in the vertical direction is gradually weakened from the center to both sides.

In terms of the Van Cittert-Zernike theorem\cite{12,13}, during the propagation of the extended light source, the spatial coherence of the two points on the intermediate plane is related to the intensity distribution of the extended light source. Assuming that the intensity distribution of the extended light source is Gaussian, so that the standard deviation of the light intensity Gaussian distribution function is used to express the size of the extended light source. In the double-slits interferometer, the coherence of the double-slits is equivalent to the visibility of the interference pattern on the CMOS camera\cite{14}.

The structure of the double-slits interferometer designed using this principle is distinctly shown in Figure 3(a). Here, $p$ is the distance from the light source to the double-slits component, and $q$ is the distance from the double-slits component to the CMOS camera. In Figure 3(a), the achromatic lens is used to modulate the wavefront of the light passing through the double-slits component to stabilize the interference pattern on the CMOS camera surface. It’s difficult to detect the amplitude of the far-field pattern without the achromatic lens, and the light path is longer. After adding the achromatic lens, the camera can be placed at the conjugate point of the light source to obtain a stable interference pattern. The achromatic lens is customized according to the design parameters from ACT508-xxx-A-ML series products of Thorlabs manufacturer. And the polarizer is utilized for obtaining the horizontal polarization light, and the filter is applied to

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**Table 1. Parameters of B8 source point.**

| Parameters                                    | Value         |
|-----------------------------------------------|---------------|
| Electron beam energy $E_e$ (GeV)              | 0.80          |
| Current $I$ (A)                               | 0.30          |
| Energy spread (RMS)                           | $4.70 \times 10^{-4}$ |
| Vertical magnetic field of BM B (T)           | 1.23          |
| Radius of BM $\rho$ (m)                       | 2.16          |
| Transverse natural emittance $\epsilon$ (nm·rad) | 36.40        |
| Theoretical horizontal beam size $\sigma_x$ ($\mu$m) | 221.90       |
| Theoretical vertical beam size $\sigma_y$ ($\mu$m) | 115.29       |
| Both beam size relative error requirement     | Below 10%     |
| $\beta_x$ (m)                                 | 0.92          |
| $\beta_y$ (m)                                 | 7.69          |
| $\varepsilon_x$                               | 1.38          |
| $\varepsilon_y$                               | -2.10         |
| $\eta_x$ (m)                                  | 0.28          |
| $\eta_y$                                     | -0.48         |

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**Figure 1.** The spectral distribution of SR at HLS-II.
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. At the same time, for the sake of facilitating the simulation, the error caused by the thermal deformation of these optical components is not considered. It is worth noting that the B8 interference system for measurements of horizontal and vertical beam size are so-called horizontal interferometer and vertical interferometer, respectively. The main difference between the two interferometers is the structural parameter of the double-slits components in the optical path, as shown in Figure 3(a).

Referring to B7 interference measurement system, we designed an interference measurement system to measure the transverse beam size of B8 source point. It should be particularly emphasized

![Figure 2. Intensity distribution of SR light with 500 nm optical wavelength. (a) Intensity distribution in both direction. (b) Intensity distribution in vertical direction.](image)

![Figure 3. The structure of the interferometers.](image)
that the horizontal interferometer and the vertical interferometer have the same spatial layout parameters, in which \( p \) is 11.50 m, \( q \) is 2.00 m, and the focal length of the lens is 1.70 m. The initial designed structure parameters of the two double-slits components are depicted in Table 2.

Compared with B7 interference measurement system, the newly designed B8 interference measurement system uses a higher resolution CMOS camera (2.5 \( \mu \)m \( \times \) 2.5 \( \mu \)m), and at the same time removes the zoom structure before the CMOS camera. Therefore, this designed B8 interference measurement system has a simpler optical path and does not have various aberrations caused by the zoom structure. The B8 system is an improvement on the basis of the B7 interferomence system. During the whole system construction process, the collimation of the beamline is a huge challenge.

For the extended light source, the double-slits interference pattern with wavelength \( \lambda \) can be described by the Fraunhofer analytical intensity formula:\textsuperscript{[15]}

\[
I = 2I_0 \sin^2 \left( \frac{\pi a}{(\lambda q) y} \right) \left[ 1 + V \cos \left( \frac{2\pi d}{(\lambda q) y} \right) \right],
\]

where \( a \) denotes the slit width, \( d \) denotes the slits-separation, \( V \) denotes the visibility of the double-slits interference pattern, which can be expressed\textsuperscript{[2]} as

\[
V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}. \tag{3}
\]

In Eq. (3), \( I_{\text{min}} \) and \( I_{\text{max}} \) are the minimum and maximum intensity of the interferogram near the central position, respectively. Assuming that the light source is spatially Gaussian distribution, yields\textsuperscript{[2]}

\[
V = \exp \left( -\frac{2\pi^2 d^2 \sigma^2}{\lambda^2 p^2} \right). \tag{4}
\]

The beam can be extracted from the measurement of \( V \), for which can be expressed as

\[
\sigma = \frac{\lambda q}{(\pi d) \sqrt{1/2\ln(1/V)}}. \tag{5}
\]
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 as follows:

\[ I(x) = a_0 + a_1 \sin c^2(a_2y + a_3)[1 + a_4 \cos (a_5y + a_6)]. \] (6)

Here, \( a_4 \) denotes the visibility of the interference pattern. In general, the size diagram of the double-slits component is distinctly described in Figure 3(b,c). It should be emphasized that the resolution of the double-slits interferometer depends on the statistical error \( dV \) of the measured visibility.\(^{[15]}\) As a consequence, the relative beam size error can be derived by

\[ |d\sigma/\sigma| = dV/(−2Vln(V)). \] (7)

Based on Eq. (7), the dependencies between the transverse beam size error and \( V \) at different visibility measurement errors \( dV \) are given, as shown in Figure 4.
It can be seen that the measurement error of the transverse beam size is insensitive to $V$ for the case that the value of visibility ranges approximately from 0.2 to 0.6. As a consequence, the visibility range of the designed interferometer should be in the range of 0.2–0.6.

3. Simulation and optimization

3.1. Design the initial structure and simulation results of the interferometers

According to the above initial designed parameters, the simulated results of the interference system using SRW code are shown in Figure 5.

The horizontal and vertical interference pattern are fitted by Eq. (6), and the resultant visibilities are obtained to be 0.481 and 0.595, respectively. Obviously, the value of $V$ is in the range discussed earlier. In this case, it can be assured that the measurement error of the beam size is insensitive to $V$.

3.2. Optimization of B8 interference measurement system

Figure 6(a,b) express the visibilities at the different slits-separations. To ensure that the visibility has a small impact on the measurement error of the beam size, the visibility $V$ should be limited within the range of 0.2–0.6. Therefore, in the horizontal interferometer, the visibility is 0.345
when $d_H$ is 6.0 mm. On the other hand, in the same analysis, the $d_V$ is chosen to be 9.5 mm in the vertical interferometer. We found that the interference pattern obtained on the CMOS camera is difficult to extract the corresponding $V$ when $d_V$ reaches 9.8 mm. As a result, the slits-separations of the interferometers are optimized as $d_H = 6.0$ mm and $d_V = 9.5$ mm.

On the basis of the determined slits-separations, we started to optimize the size of the small holes in the double-slits component. Figure 6(c,d) shows the effect on $V$ and the center intensity of the interference pattern when $L_{Hy}$ and $L_{Vx}$ are changed. It can be seen that the variation of these two parameters has little impact on $V$. In order to ensure that the system can operate under low intensity, the optimum size of $L_{Hy}$ and $L_{Vx}$ are both chosen as 10.0 mm.

In the same way, we continued to optimize the important parameters of $L_{Hx}$ and $L_{Vy}$, and the results are shown in Figures 7 and 8. It is pointed out that the number of fringes in the interference pattern should be as many as possible, and the center intensity should be as large as possible. Based on this design specifications, the values of $L_{Hx}$ and $L_{Vy}$ are determined to be 1.0 mm and 2.0 mm, respectively.

In terms of system optimization and numerical analysis, the final designed parameters of B8 interference measurement system are summarized in Table 2.

According to the optimal parameters given in Table 2, we performed the simulation again, and the results obtained are shown in Figure 9. By fitting the interference pattern data of the horizontal and vertical interferometer, the corresponding visibilities are acquired to be 0.345 and 0.548,
respectively. It is concluded that the horizontal beam size is 218.49 μm, and the vertical beam size is 105.71 μm. In general, the design of B8 interference system meets the current actual needs.

4. Conclusions

In this paper, the SRW code is used to calculate synchrotron radiation and obtain the intensity distribution of B8 source point based on the relevant machine parameters of HLS-II. And then, according to the characteristics of the light source obtained from simulation, a double-slits interferometer using visible light was selected. Due to the spatial characteristics of the B8 beamline, we designed two interferometers with the same optical path layout to constitute a beam size measurement system for B8 source point. Finally, the slits-separations $d_H$ and $d_V$ are optimized to be 6.0 mm and 9.5 mm. And the size parameters $L_{Hx}$, $L_{Vx}$, $L_{Hx}$, and $L_{Vy}$ of the double-slits components are optimized to 10.0 mm, 10.0 mm, 1.0 mm, and 2.0 mm, respectively. At this time, the visibilities of the horizontal and vertical interferometer are achieved as 0.345 and 0.548, respectively, within the range of 0.2–0.6. This is of guiding significance to the subsequent optimization and improvement of the experimental system performance. We plan to carry out related experiments on HLS-II in the next research work, which can verify the reliability and applicability of the designed interference measurement system while meeting the actual needs of the project.
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Figure 9. Simulated results of the optimized interferometers.
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