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FEASIBILITY STUDY OF BEAM SIZE MEASUREMENT USING INTERFEROMETER TECHNIQUE FOR ALS-U*

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Abstract

ALS-U is an ongoing upgrade of Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory. The upgraded ALS will replace the existing Triple-Bend Achromat (TBA) storage ring lattice with a compact Multi-Bend Achromat (MBA) lattice. This MBA technology allows us to tightly focus electron beams down to about 10 µm to reach diffraction limit in a soft x-ray region. The beam size measurement is a challenging task for this tightly focused beam. The interferometer technique with visible light from synchrotron radiation has been developed in many facilities to measure their beam size at a micrometer-level accuracy. In this paper, we will present the feasibility study of this technique for the ALS-U storage ring beam size measurement.

INTRODUCTION

Advanced Light Source Upgrade (ALS-U) is an on-going upgrade project at Lawrence Berkeley National Laboratory which will provide x-ray beams at least 100 times brighter than those of the existing ALS [1]. The upgraded ALS will occupy the same facility as the current ALS, replacing the Triple Bend Achromat storage ring lattice with a compact Multi-Bend Achromat lattice which has a tightly focused beam of about 10 µm in both horizontal and vertical directions. The accurate beam size measurement of this small beam is a challenging task. Several techniques have been developed in many synchrotron light source facilities to measure a small beam size with a micrometer-level accuracy. Among these techniques, the interferometer with visible light from synchrotron radiation is the most powerful and simple method to resolve a small beam size.

The interferometer technique was first applied to measure electron beam size by Mitsuhashi at the ATF damping ring [2, 3]. Nowadays, it has become a common method to measure electron beam sizes for synchrotron light sources. At ALS-U, we plan to use this technique to measure electron beam size for the storage ring. In this paper, we present the feasibility study of this technique to measure the ALS-U beam size with a micrometer-level accuracy.

INTERFEROMETER TECHNIQUES

The working principle of the interferometer technique has been well discussed in papers [2,3]. Here we give a brief description of this technique and introduce formulas that will be used in our studies.

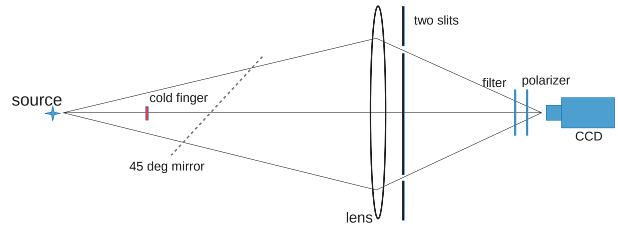

Figure 1: Sketch of the interferometer setup for beam size measurements.

According to the Van Citterut-Zernike theorem, the profile of an object is given by the Fourier Transform of the complex degree of spatial coherence γ at longer wavelengths as in the visible light. Therefore, the beam profile and the beam size can be derived from a measured spatial coherence. The spatial coherence can be measured using a wavefront-division type of two-slits interferometer with polarized quasi-monochromatic light as shown in Fig. 1. When the focused beam passes through the two slits, it will create interference fringes on the image plane. Assuming the two slits are illuminated with the same intensity, the interference fringes can be calculated by

$$I(x) = I_0 \left[\mathrm{sinc}\left(\frac{2\pi a}{\lambda R} x + \phi\right) \right]^2 \left(1 + |\gamma| \cos\left(\frac{2\pi D}{\lambda R} x + \psi\right) \right), \tag{1}$$

where I_0 is the light intensity through the slits, a is the half width of the slit, R is the distance between the two slits and the image plane, λ is the working wavelength, and D is the separation of the two slits; ϕ and ψ are phase shifts; $|\gamma|$ known as visibility is the real part of the complex degree of spatial coherence γ. It is defined as $|\gamma| = (I_{max} - I_{min})/(I_{max} + I_{min})$, where I_{max} and I_{min} are the maximum and minimum intensities of the interference fringes. Assuming the electron beam has a Gaussian distribution, the visibility is related to the beam size according to

$$\sigma = \frac{\lambda L}{\pi D} \sqrt{\frac{1}{2} \ln \frac{1}{|\gamma|}}, \tag{2}$$

where σ is the RMS beam size and L is the distance between the source point and two slits. D/L will define the acceptance angle of these two slits. Therefore, by measuring and fitting the interference fringes to obtain the visibility $|\gamma|$, we can derive the beam size information σ.

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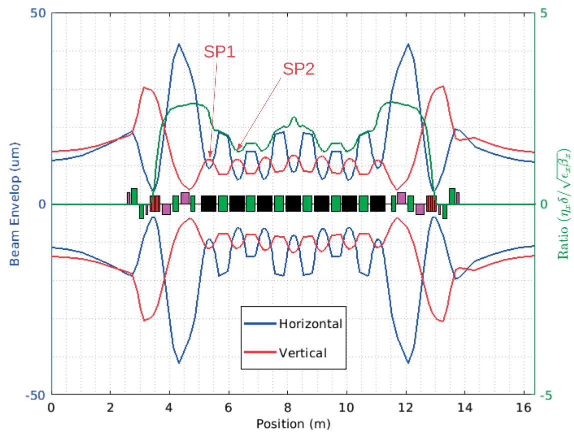

Figure 2: Beam size envelopes for ALS-U storage ring. The ratio between the dispersion induced beam size and Betatron oscillation beam size is also shown in the plot. Two sources points at different ratio of these two beam sizes are indicated.

SIMULATIONS AND REQUIREMENTS

The ALS-U storage ring will be operated at full coupling resonance to generate a round electron beam. The envelopes of one sigma beam size along the ring are shown in Fig. 2. At straight sections, the beam size is about 10 µm in both horizontal and vertical directions. Inside the arc the beam size varies with location and is about 10 µm at bending magnet locations. To measure this 10 µm beam size with the interferometer technique, we first carry out simulation studies using Sychrotron Radiation Workshop (SRW) code [4]. Fig. 3 shows an example of simulated interference fringes created by two slits with the acceptance angle of 6.2 mrad for 10 µm beam size. The intensity profile shows that the ratio between the maximum and minimum intensities I_{min}/I_{max} is 26%. Therefore, the visibility of the interference fringes $|\gamma|$ is about 58%, which is consistent with the result calculated from Eq. (2). For a given beam size, the optimal region for the visibility measurement is about 50%. According to Eq. (2), the relationship between the visibility and beam size are plotted in Fig. 4 for different acceptance angles of two slits. In order to have a 50% visibility for a 10 µm beam, the required acceptance angle is about 8 mrad. For a smaller beam size, an even larger acceptance angle of two slits is required to have the optimal visibility.

To measure both beam emittance and energy spread, two radiation source points are required. These two source points need to have different dominating beam size contributions from either Betatron oscillation or dispersion functions. For the ALS-U storage ring, the dispersion induced beam size dominates the overall horizontal beam size as shown in Fig. 2. This makes it difficult to accurately measure horizontal emittance. For example, if we want to achieve 20% relative accuracy of the emittance measurement, the beam size measurement accuracy needs to be 3%. For 10 µm beam, this requires the beam size measurement accuracy is about 0.3 µm, which could be very challenging.

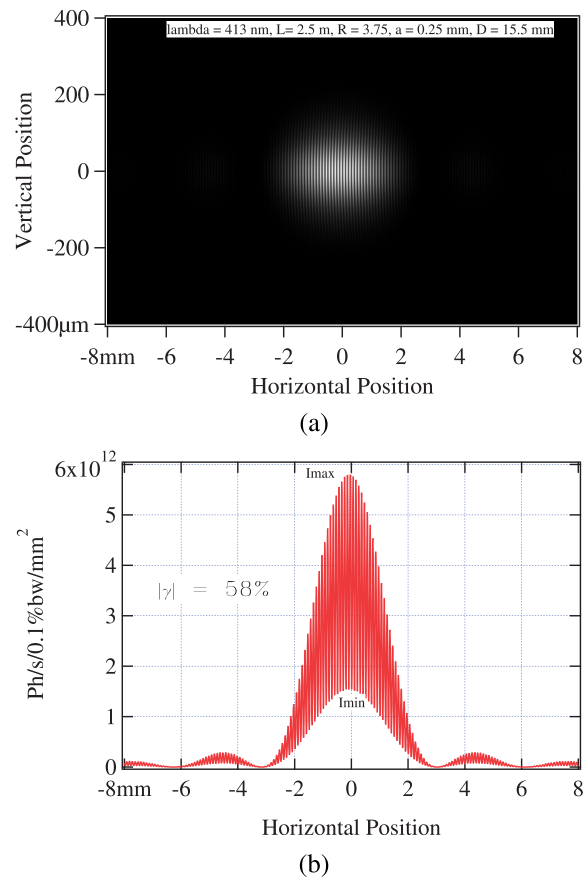

Figure 3: The simulated interference fringes for the ALS-U beam size measurement. (a) The interference fringe at the image plane, (b) the intensity profile of the interference fringes.

MEASUREMENT ERRORS

Beam size measurement errors can be classified into two types: systematic error and statistical error. The systematic errors are caused by the depth of field effect, alignment errors, intensity imbalance and so on. These errors can be eliminated by accurate modeling and careful alignments. However, the statistical errors cannot be removed. They are caused by the CCD noise, beam jitter, beamline vibrations and others. Here, we are focusing on the statistical errors of beam size measurements. These errors $\Delta\sigma$ are propagated from the visibility measurement errors $\Delta|\gamma|$ according to the formula

$$\Delta\sigma = -\frac{1}{\sqrt{8}}\frac{\lambda L}{\pi D}\frac{1}{|\gamma|\sqrt{\ln\frac{1}{|\gamma|}}}\Delta|\gamma|. \qquad (3)$$

Assuming the visibility measurement error $\Delta|\gamma|$ is about 0.025, the beam size measurement error as the function of the beam size are shown in Fig. 5 for different acceptance angle of two slits. To achieve 1 µm level accuracy for the 10 µm beam size, 3-4 mrad acceptance angle is required. To

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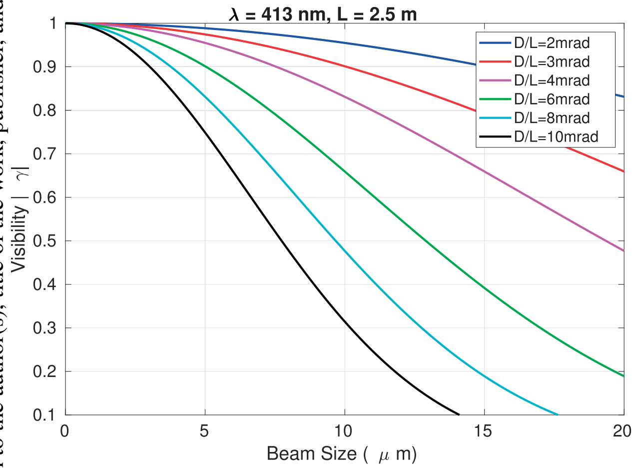

Figure 4: Visibility $|\gamma|$ as the function of the beam size for different acceptance angles of two slits.

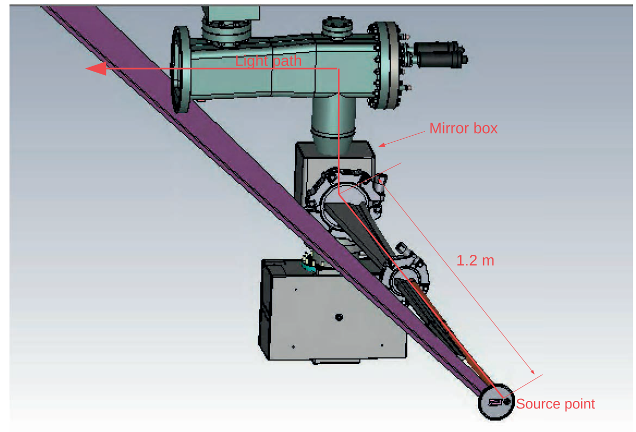

Figure 6: A preliminary design of the diagnostic beamline based upon the ALS-U infrared beamline.

have the accuracy at the level of 0.3 µm, about 8-10 mrad acceptance angle is required. However, the measurement accuracy cannot be further improved when the acceptance angle is larger than 10 mrad because increasing acceptance angle will decrease the visibility. As a result, the measurement accuracy is reduced according to Eq. (3). In this case, if we want to further increase the beam size measurement accuracy, we need to reduce the visibility measurement error $\Delta|\gamma|$. In the above discussion, we are assuming $\Delta|\gamma| = 0.025$, which is a good assumption, but can be decreased by reducing CCD noise, beam jittering and beamline vibrations effects.

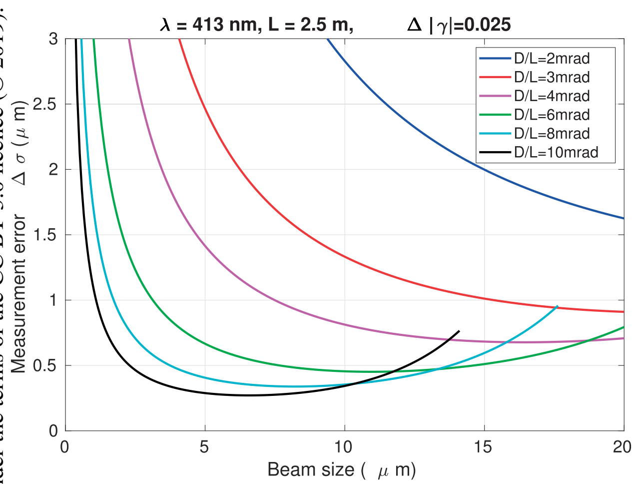

Figure 5: Beam size measurement error $\Delta\sigma$ as the function of the beam size at different acceptance angles of two slits.

BEAMLINE DESIGN

All the beam size measurements described above will greatly benefit in terms of measurement accuracy from a large angular acceptance beamline. For achieving a micrometer-level accuracy, therefore it is crucial to design a diagnostic beamline with a large acceptance angle. Our preliminary layout for the diagnostic beamline is based on the vacuum chamber and synchrotron light port designed for the ALS-U infrared beamlines which has a 14 mrad maximum acceptance as shown in Fig. 6. It includes a first silicon carbide (SiC) mirror at 45 degree, about 1.2 m away from the source point, which will be used to collect the radiation from a bending magnet. The mirror can be mounted on a water-cooled copper holder, and a cold finger right in front will be used to stop the x-rays, minimizing the heat load on the downstream mirror. The size of such optics and their distance from the radiation source ultimately set the maximum acceptance angle of the beamline, therefore the best resolution. With a total acceptance angle of 12 mrad, we would be able to collect most of the visible light from the source. At a distance of 1.2 m, the first rectangular mirror would have to have a size larger than 15 × 22 mm. The radiation will be first reflected vertically. A second mirror, at about 50 cm from the first one, will then deflect the light vertically again. Such a setup is needed to avoid interference with a nearby x-ray beamline. Right after the first mirror, a baffle system will be used to control the horizontal acceptance angle and limiting the depth of field effect. After the second mirror, we will first place a window for transitioning from high vacuum to a lower vacuum chamber, followed by an optical lens and two slits which will image the source to the CCD plane with a magnification greater than one.

CONCLUSIONS

At ALS-U, we plan to use interferometer technique to measure the storage ring beam size with a micrometer-level accuracy. In this paper, we present the feasibility study of this technique, including SRW simulations, measurement requirements and errors as well as the beamline design consideration. Guided by this study, we are designing the diagnostic beamline for the ALS-U storage ring.

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