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DIAGNOSTICS BEAMLINE DEVELOPMENT FOR ALS-U*

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Abstract

The Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory is currently undergoing an upgrade known as ALS-U. As part of this upgrade, the existing Triple-Bend Achromat (TBA) storage ring lattice is being replaced with a Multi-Bend Achromat (MBA) lattice, which allows for the tight focusing of electron beams to approximately 10 µm, reaching the diffraction limit in the soft x-ray region. However, accurately measuring the beam size in such a tightly focused beam presents a challenge. This paper presents a diagnostics beamline design for ALS-U that utilizes a 2-slit interferometer technique to achieve a sub-micron resolution for beam size measurement. The impact of beam jitter, optics vibration as well as the incoherent depth-of-field effect on the measurement are also discussed.

INTRODUCTION

The Advanced Light Source Upgrade (ALS-U) project, currently underway at Lawrence Berkeley National Laboratory, aims to provide x-ray beams that are at least 100 times brighter than those produced by the existing ALS facility [1]. This upgrade involves replacing the existing Triple Bend Achromat storage ring lattice with a new compact Multi-Bend Achromat lattice capable of tightly focusing electron beams down to approximately 10 µm in both the horizontal and vertical directions. However, accurately measuring the size of such a small beam is a challenging task, and many synchrotron light source facilities have developed techniques to measure beam size with a high degree of accuracy. Among these techniques, the use of an interferometer with visible light from synchrotron radiation is a powerful and simple method for resolving small beam sizes.

Initially developed at the KEK ATF damping ring [2, 3] to measure electron beam size, the interferometer technique has become a common method for measuring electron beam sizes at 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 a diagnostic beamline design for ALS-U that utilizes the 2-slit interferometer technique to achieve a micrometer-level accuracy for beam size measurement. This paper begins with a brief introduction to the 2-slit interferometer technique and an estimation of its measurement error. Subsequently, we present the ALS-U beamline design and examine how measurement is impacted by beam jitter, optics vibration, and the incoherent depth of field effect (IDOF).

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INTERFEROMETER TECHNIQUES

Previous papers [2, 3] have extensively discussed the interferometer technique for measuring electron beam size. In this study, we briefly describe the technique and present the formulas that we will use. As shown in the Fig. 1, the technique involves passing a focused beam through two slits, which results in interference fringes on the image plane. The intensity of these fringes can be calculated using equation

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

where I_0 is the intensity of light through the slits, a is the half width of the slit, R is the distance between the slits and the image plane, λ is the working wavelength, D is the separation of the two slits, ϕ and ψ are phase shifts, and $|\gamma|$ is the visibility. The visibility is the real part of the complex degree of spatial coherence γ, and 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. If the electron beam has a Gaussian distribution, the visibility is related to the beam size according to equation

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

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

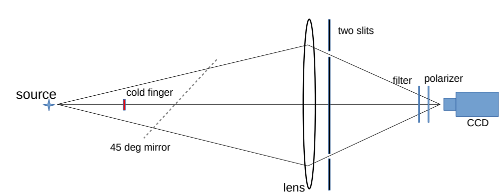

Figure 1: Sketch of the 2-slit interferometer setup for beam size measurements.

MEASUREMENT ERRORS

The accuracy of beam size measurements is affected by various factors, such as CCD noise, beam jitter, and beamline vibrations. The resulting errors, denoted by $\Delta\sigma$, are related to the errors in visibility measurements, $\Delta|\gamma|$, by the formula

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

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Assuming a visibility measurement error of 0.01, Fig. 2 shows the beam size measurement error as a function of beam size for different acceptance angles of two slits. Achieving an accuracy of 0.2 µm for a beam size of around 10 µm requires an acceptance angle of approximately 6 mrad.

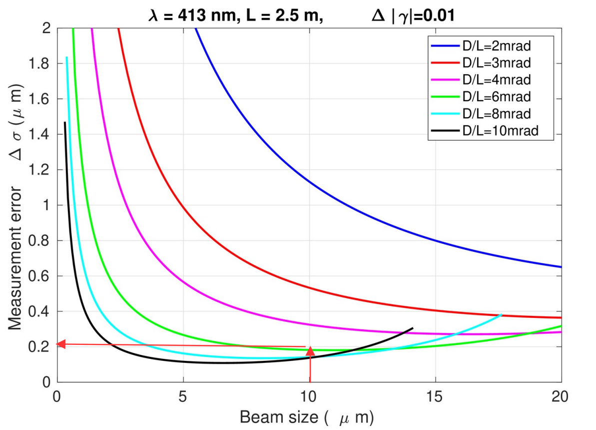

Figure 2: Beam size measurement error $\Delta\sigma$ as the function of the beam size at different acceptance angles of two slits.

Ideally, two diagnostic beamlines at different source points are needed to measure both beam emittance and energy spread independently. These two source points should have different dominant beam size contributions from either Betatron oscillation or dispersion functions. Due to cost and space constraints, a single diagnostic beamline will be built based on dipole 7, sharing the similar front-end vacuum system design as the IR user beamline. The energy spread will be measured independently with a extracted beam at the Storagre-Ring-to-Accumulator (STA) transferline with less than 5% resolution.

At the source point, the dispersion-induced beam size dominates the overall horizontal beam size, as shown in Fig. 3. This makes it challenging to measure horizontal emittance accurately. For instance, achieving a 20% relative accuracy of the emittance measurement in the horizontal direction requires a beam size measurement accuracy of 3% according to equation

$$\sigma = \sqrt{\epsilon\beta + (\eta\delta)^2} \rightarrow \frac{d\epsilon}{\epsilon} = 2(1 + (\eta\delta/\sqrt{\epsilon\beta})^2)\frac{d\sigma}{\sigma}, \quad (4)$$

where $\eta\delta/\sqrt{\epsilon\beta}$ is 1.29 as shown in the Fig. 3. For a 10 µm beam, this necessitates a beam size measurement accuracy of approximately 0.3 µm.

BEAMLINE DESIGN

To achieve high accuracy at a sub-micrometer level, it is vital to design a diagnostic beamline that can accept a large angle of radiation (Fig. 4). In the case of ALS-U, the acceptance angle is determined by the beam egress chamber in the front end, which is 16.5 mrad x 11 mrad. The design of the beam egress vacuum chamber is similar to that of the infrared user beamlines. Downstream the egress chamber it

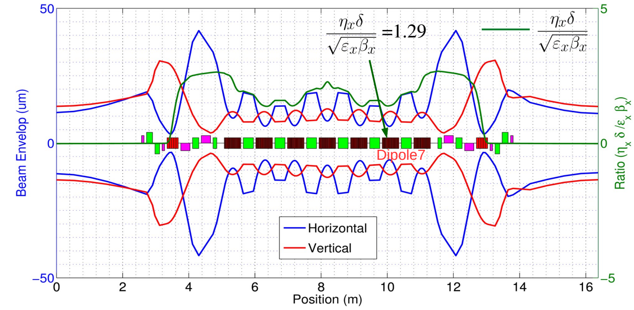

Figure 3: Beam size envelopes for ALS-U storage ring. The ratio between the dispersion induced beam size and Betatron oscillation beam size is also shown in the plot.

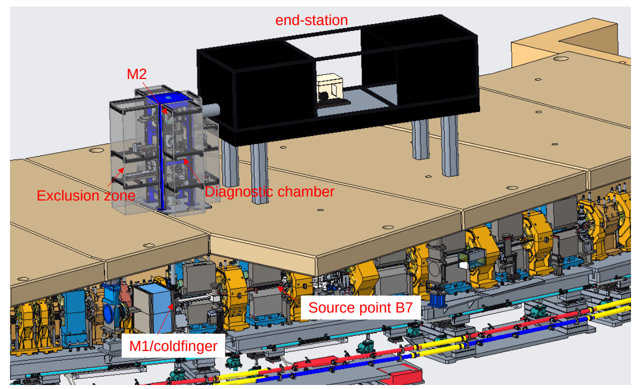

Figure 4: CAD model of the ALS-U storage ring diagnostics beamline.

is the M1 chamber, containing a Silicon Carbide (SiC) mirror located 1.378 m away from the source point. This mirror collects radiation from a bending magnet at a 45-degree angle and is mounted on a water-cooled copper holder. A cold finger positioned in front of the mirror stops x-rays to reduce the heat load on the M1 mirror. The total acceptance angle of 16.5 mrad x 11 mrad mrad enables the collection of most visible light from the source, which is deflected vertically to the rooftop of the ring tunnel. The cold finger is fully extractable and can track the vertical position of the electron beam with a resolution of 10 µm. A vacuum window separates the M1 chamber and the low vacuum diagnostics chamber downstream, which contains lense, apertures, and slits/obstacles that are fully extractable to allow the transmission of unfocused beams to the endstation if needed. The second M2 mirror is located downstream of the diagnostics chamber, deflecting the beam to the endstation. It has pitch- and yaw-adjustable movements to align the beamline (Fig. 5). The endstation is equipped with multiple cameras for different measurement purpose.

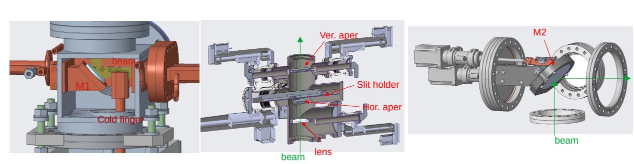

Figure 5: CAD models for the M1 chamber (left), diagnostics chamber (middle) and M2 chamber (right).

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BEAM JITTER AND OPTICS VIBRATIONS

When a beam jitters, the interference fringe experiences a phase shift, resulting in reduced visibility. The following equation shows that the phase shift ($\Delta\phi$) is proportional to the displacement (Δx) of the beam,

$$\Delta\phi = \frac{2\pi}{\lambda}\frac{D}{L}\Delta x, \quad (5)$$

where λ, D, and L are the wavelength, distance between the 2-slit and camera, and distance between the 2-slit and the source point, respectively. By integrating the interference intensities over the phase shift, the average visibility can be calculated using equation

$$|\bar{\gamma}| = sinc(\Delta\phi)|\gamma|, \quad (6)$$

where γ is the complex amplitude of the interfering waves and *sinc* is the sinc function. For the specific values of $L = 3.3$ m, $D = 34$ mm, $\lambda = 430$ nm, and beam jitter $\Delta x = 1.5\,\mu$m, the error due to beam jitter is calculated to be $\Delta|\gamma| = 0.0085$, which is below the assumed error of 0.01.

The impact of vibrating optics can be represented as the virtual vibration of the beam (Fig. 6). The amplitude of the virtual vibration depends on whether the optics is a lens or a mirror. For a beam with a size of around 6000 nm, the equivalent virtual vibration (Δx) should be less than 5%. Therefore, the optics vibration (Δx_0) should be less than 300 nm for a lens (with magnification factor, M=1) and less than 600 nm for a mirror, which defines the vibration requirement for our beamline design.

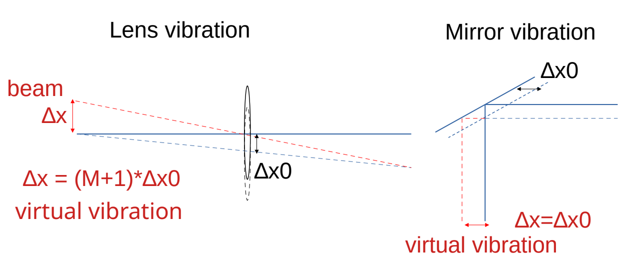

Figure 6: Effect of optics vibration from lens (left) and mirror (right).

INCOHERENT DEPTH OF FIELD EFFECT

As studied in paper [4,5], the interferogram in the horizontal plane is affected by the incoherent depth of field (IDOF) effect, which is caused by the instantaneous opening of the synchtrotron radiation in that plane. The IDOF has two main effects: first, the apparent size of the horizontal beam becomes larger, and second, the visibility of the horizontal interferogram is reduced due to an intensity imbalance at the double slit opening. We have studied these effects using both formulas [4, 5] and the new verison SRW code [6]. According to theory, the apparent beam size is larger than the real beam size, resulting in a reduced visiblity therefore the beam size measurement resolution as shown in Fig. 7. Assuming the 1% (shot-to-shot) measurement resolution for visibility, the measurement resolution for a 7 um beam is only about 10% (0.7 um), resulting in a 50% emittance resolution. However, multiple shots and multiple slit separations could lead to higher resolution. SRW simulations show that the IDOF effect may be overestimated by the theory, and its impact on beam size measurement could be much smaller. We are currently investigating the discrepancy between the theory and simulation.

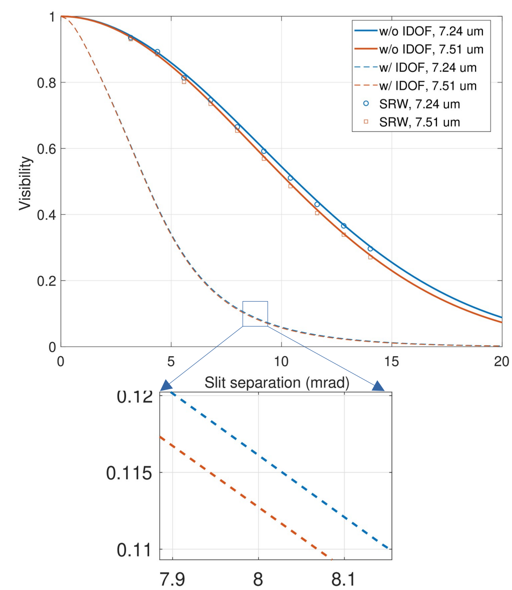

Figure 7: Visibility as function of slit with and without IDOF by theory and SRW simulations.

CONCLUSIONS

At ALS-U, we are currently in the process of designing a synchrotron radiation diagnostics beamline that will be based on a 2-slit interferometer technique. We has conducted studies on measurement errors, beam jitter, and optics vibration. By taking these factors into account, we have found that a sub-micrometer-level accuracy can be achieved. We have also studied the effects of incoherent depth of field (IDOF) using both theory and SRW simulation, and we are currently investigating the discrepancy between the two.

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