A nanoradian x-ray beam deviation-correction device for x-ray free electron laser oscillator

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Abstract. An energy-recovery linac (ERL)-based x-ray free electron laser (X-FEL) combined with a low-loss x-ray optical cavity can produce a high-intensity and fully coherent x-ray beam. The idea is to let the x-ray emission beam in the cavity become the seed beam of the FEL to realize x-ray stimulated emission conditions. Because the electron bunch size in the ERL is sub-micrometer and the x-ray cavity crystals are a few tens of meters away from the electron bunch, a deviation of a few nanoradians in the beam direction can cause the seed beam miss the electron bunches. Therefore, it is necessary to develop a high-precision beam-direction correction device that is independent of the x-ray cavity tuning to ensure collision of the narrow x-ray seed beam and electron bunches. To this end, we have assembled a pair of x-ray prisms on two rotary stages. We operated the device using 1.086 Å wavelength x-rays and demonstrate that the angular resolution can reach 1 nrad within a deviation range of ±3.1 mrad.

1. Introduction
After self-amplified spontaneous emission (SASE) free-electron lasers (FELs) in the hard x-ray region were under construction, Kim et al.¹ proposed the x-ray FEL oscillator (X-FELO), which is a multi-gigaelectronvolt energy-recovery linac (ERL) combined with an undulator and low-loss x-ray cavity. The amplified x-ray pulse at the end of the undulator is reflected back to the entrance of the FEL where it meets a fresh electron bunch, and the process is repeated to increase the intensity. The peak power of the X-FELO is low but the radiation has a narrow bandwidth and a high photon spectral intensity. The fully coherent x-ray radiation of the X-FELO is expected to be a valuable new scientific tool in various research fields.

While the FEL machine itself is large (with a possible x-ray cavity of order of 100 m), the electron bunches in the undulator are of a sub-micrometer extent. For the electron bunches and beam to collide effectively, it is necessary to either adjust the bunch position in the perpendicular plane to within a resolution of 10 nm or tune the x-ray beam in two perpendicular directions with an angular resolution of 2 nrad.

The beam angle can be adjusted by tuning the cavity crystals; however, two crystals must be tuned simultaneously to maintain the resonant condition, which while possible, is technically difficult. In this report, we propose a beam tuning method independent of the x-ray cavity tuning. We designed Be prisms with a refracting angle of 30° and measured the x-ray absorption factor and refractive index. We found there is impurity of iron in the Be prisms, its K-absorption edge could affect reflectivity of the x-ray cavity at the spectrum of 7.1keV. We assembled a deviation-correction device using a pair of Be prisms, characterized its performance, and evaluated the resolution of the angular correction.
2. Principle and equipment
A visible light beam can be refracted by a refracting prism and the same principle is valid for x-rays. Because the refractive index \( n \) for x-rays is less than but close to unity, the beam is refracted in the direction opposite to that for visible light as shown in figure 1(a). The refracted angle \( \Delta \) in this case is approximately \( 10^{-6} \) rad. Letting the prism rotate about the incident direction means the trajectory of the refractive beam will describe a cone with an apex angle of \( 2\Delta \). We use a pair of prisms as shown in figure 1(b) for which the beam refraction in the horizontal direction is cancelled and that in the vertical direction is \( 2\Delta \sin(\omega) \), where \( \omega \) is rotation angle of the prisms. Photographs of a Be prism and the rotary stages are shown in figure 2.

![Figure 1](image1.png)

(a) X-ray beam refraction through a Be prism. (b) Principle of x-ray direction correction by a pair of Be prisms.

The refractive index can be expressed as \( n = 1 - \delta \), where \( \delta = \frac{\rho_0 A_r^2 Z_{Ar} N_A}{2\pi} \times N_{Ar} \), \( \rho \) is the Be density, \( r_0 \) is the classical electron radius, \( \lambda \) is the x-ray wavelength, \( Z \) is the atomic number, \( A_r \) is the atomic weight, and \( N_{Ar} \) is Avogadro’s number. Following Snell’s law, \( \Delta \) in figure 1(a) is given as \( \Delta = \delta \times \tan 30^\circ \). Therefore, the refractive beam direction will be a function of the rotation angle \( \omega \), i.e., it will vary as \( 2\Delta \sin(\omega) \).

3. Experiments and results
We considered three characterization experiments of the Be prisms at the Photon Factory. We first rotated the two Be prisms stages (changed the angle \( \omega \)) and confirmed that the refractive beam behaves as sinusoidal function of \( \omega \) using a self-referenced comparator. The observed results and a sinusoidal fit function are shown in figure 3 for an x-ray wavelength of 1.086 Å. The maximum
correction angle is ±3.18 μrad, which corresponds to a δ value of 2.67 × 10⁻⁶; the calculated value from the fit is 2.6 × 10⁻⁶. A line fit of a partial sin (ω) curve gives a slope of 56 nrad/degree, which

indicates that the correction device can adjust the beam deviation with a nanoradian resolution. We also measured the x-ray absorption of the Be prism from 21 to 5 keV. The observed linear x-ray absorption coefficients are shown in figure 4. The calculated values are fairly consistent with the measured data except in the energy region below 7.1 keV because of the Fe K-absorption edge structure. The Be material used for the prisms is considered to contain Fe as an impurity, which is also present in the Be window of the beamline.

In the 8 to 20 keV region, we measured the refractive index of the Be prism using a 111 Si crystal.

Figure 3. Sinusoidal behavior of the observed beam directions through a pair of Be prisms. A sinusoidal fitting is also shown. Following the rotation angle ω, the x-ray beam direction is refracted up and down and behaves like a sine function of angle ω. The angular resolution of the x-ray angle measurement system is 5 nrad. The fit for a partial sin(ω) curve gives a slope of 56 nrad/degree, which means that the correction device can adjust the beam direction with a nanoradian resolution.

Figure 4. (a) observed and calculated x-ray linear absorption coefficient (mm⁻¹) of the Be prism from 5–21 keV. (b) enlarged view of the Fe K-edge absorption structure at 7 keV. The same structure is also observed from the Be window on the beamline.

Figure 5. Observed and calculated x-ray beam refractive angle as a function of x-ray energy.
4. Conclusion

We have assembled a nanoradian correction device for x-ray direction deviation using a pair of Be prisms and confirmed that the device can adjust the beam direction with a resolution of 1 nrad within a deviation range of ±3.1 µrad. The thickness of the prism 0.5 mm from the edge is approximately 0.29 mm, which attenuates the beam intensity by about 2.5%. Therefore, two Be prisms attenuate the intensity by 5%.

Because there is a gap between the two prisms, the center of the beam will be spatially shifted during correction. The magnitude of the shift is proportional to the size of the gap: a gap of 10 mm will shift the beam center by 15 nm, and narrowing the gap will reduce the beam shift. The correction time response depends on the rotation speed of the prism; a rotation speed of 18°/s corresponds to an angular correction response time of 100 nrad/s.

Both the Be prisms and the Be window of the beamline contain Fe impurities, as evidenced by the Fe K-absorption spectra observed at 7.1 keV.

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