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Requirements for Grazing-Incidence Mirrors for a Hard X-ray Free-Electron Laser Oscillator*

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XFELO and Optical System Requirements

An x-ray free-electron laser oscillator (XFELO), making use of crystals and high-reflectivity mirrors and ultra-low-emittance multi-GeV electron beams, will produce coherent x-rays with extremely narrow bandwidth (a few meV) and high peak and average brightness [1].

Two highly-reflective (R>95% per mirror) elliptical, grazing-incidence mirrors are required to adjust the XFELO mode profile for maximum gain and to collimate the angular divergence impinging on crystals to less than 0.2 μr rms (Fig. 1).

Wave optical calculations, using measured surface metrology data, have been used to determine the performance and surface quality requirements of the XFELO mirrors.

XFELO Cavity Mirror System

Although the scheme illustrated below using two crystals is non-tunable, a broadly tunable arrangement is feasible using four crystals [2].

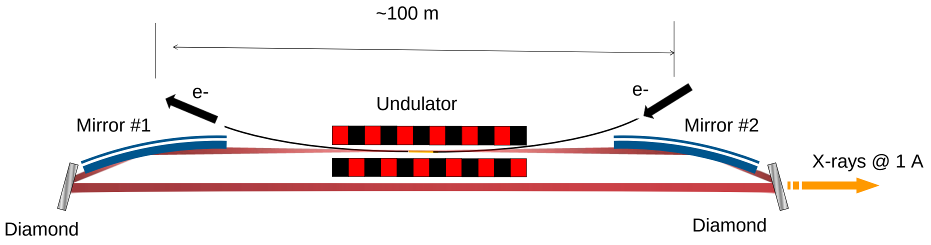

Fig. 1: Optical layout.

Wave Optical Simulation Code

The planar simulation code used in this work was a version of the code described in Ref [3], modified to take into account the complex field distribution of an FEL source.

Figure 2 shows the simulation geometry. The complex wavefield downstream of the mirror is evaluated directly, by propagating waves from the FEL source to the mirror using the Huygens-Fresnel-Kirchhoff construction

$$E_{\mathrm{mir}}(x_{\mathrm{m}}) = -\frac{\mathrm{i}}{\lambda}\int_{\mathrm{source}} E_{\mathrm{source}}(x_{\mathrm{s}})\frac{\mathrm{e}^{ik\cdot r(x_{\mathrm{s}},h(x_{\mathrm{m}}))}}{\sqrt{r(x_{\mathrm{s}},h(x_{\mathrm{m}}))}}\chi(x_{\mathrm{s}},\Delta h(x_{\mathrm{m}}))\,\mathrm{d}x_{\mathrm{s}},$$

where χ is the obliquity factor representing the directivity of the secondary sources. The field reflected from the mirror, E_{refl}, is calculated using the Kirchhoff theory, wherein the complex Fresnel reflectivity is obtained using the tangent plane approximation [4]:

$$E_{\mathrm{refl}}(x_{\mathrm{m}}) = [1 + R(x_{\mathrm{s}},\Delta h(x_{\mathrm{m}}))]E_{\mathrm{mir}}(x_{\mathrm{m}}).$$

The field at the detection plane E_{det} is calculated by treating each point on the mirror as a secondary source whose amplitude and phase depends on the reflectivity R and the incident field E_{mir}

$$E_{\mathrm{det}}(x_{\mathrm{d}}) = -\frac{\mathrm{i}}{\lambda}\int_{\mathrm{mirror}} E_{\mathrm{refl}}(x_{\mathrm{m}})\frac{\mathrm{e}^{ik\cdot r'(h(x_{\mathrm{m}}),x_{\mathrm{d}})}}{\sqrt{r'(h(x_{\mathrm{m}}),x_{\mathrm{d}})}}\chi(\Delta h(x_{\mathrm{m}}),x_{\mathrm{d}})\,\mathrm{d}x_{\mathrm{m}}.$$

Multiple scattering and surface shadowing effects were neglected.

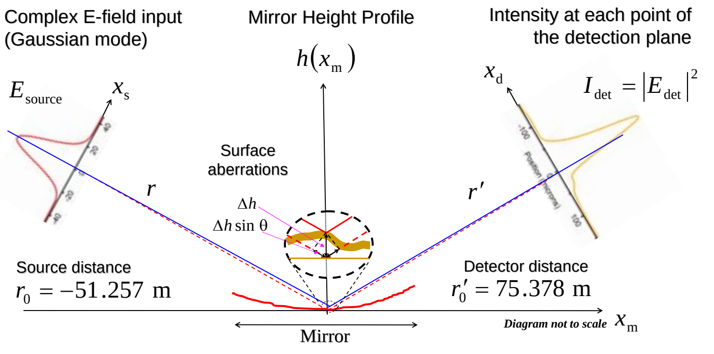

Fig. 2: Simulation geometry for wavefield calculations.

Simulations and Results

The complex electric field leaving the FEL source (assumed to be a fundamental Gaussian mode) was computed for 0.1-nm wavelength.

Silica was chosen as the mirror material. The effect of heat load was ignored. The parameters are as follows: Length= 0.4 m, sampling distance= 0.5 mm, mirror angle=1 mrad.

The simulated mirror height profile was constructed by adding to the height profile of an ideal elliptical mirror a 1-D surface error profile extracted from 2-D data measured for a real mirror. Only one mirror was simulated. We modeled a range of mirror surface qualities by applying a scaling factor to the figure error profile used in the simulation.

Consistent with the Debye Waller factor, the surface figure error for one mirror should be <2 nm rms, and slope error <0.21 μrad rms to achieve the required round-trip reflectivity of 95% (Fig. 3). However, the quality of the propagated collimated beam to the first monochromator is strongly dependent on the frequency content of a mirror surface (Fig. 4).

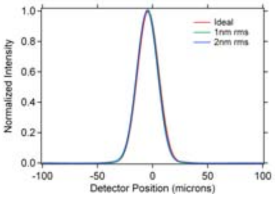

Fig. 3: Normalized intensity at the focus vs. surface error.

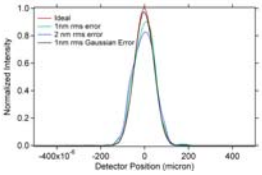

Fig. 4: Normalized collimated intensity vs. surface error.

Simulation with SRW[5] Using a Thin Lens Model

Similar to a visible optics lens, an aberration-free aspheric X-ray mirror produces an apertured spherical wavefront converging to a diffraction-limited focus. The phase aberrations resulting from mirror surface imperfections may be included in the pupil function. Figure 5 shows the results. The two simulation methods agree quite well. Minor differences are to be expected because of the differences in the modeling and the data input. Moreover, here the reflectivity is assumed to be equal to unity. These issues will be addressed in a future work.

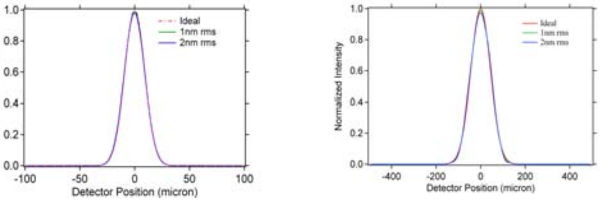

Fig. 5: Normalized focused intensity (left) and collimated intensity (right) vs. surface figure error.

Conclusions

The XFELO grazing-incidence mirror requirements are challenging. Our simulations show that the surface figure error of each mirror should be <2 nm rms with a slope error < 0.21 μrad rms, in order to provide the >95% round-trip reflectivity required for the XFELO system to operate. The performance strongly depend of the spatial frequency content of the mirror surface profile. The two simulation methods reasonably agree. Here the monchromators are assumed to be ideal. Further work is need to reliably determine the mirror quality. specifications.

Acknowledgements:

*The research at Argonne is supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

L Assoufid gratefully acknowledges J.Qian for his assistance with the mirror surface measurements

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