INVESTIGATING THE EFFECT OF MIRROR IMPERFECTIONS IN PHOTON TRANSPORT SYSTEMS FOR FELS

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Abstract

Imperfections on the surfaces of the optical components of photon transport systems can degrade the quality of the radiation, causing amongst other effects structure in the transverse beam profile. This effect is being investigated for one of the beamlines at FLASH. The FEL mirror surfaces have been measured in the metrology laboratory at Helmholtz Zentrum Berlin / BESSY-II, and these data are input into wavefront propagation calculations, which model the transport of the radiation field from the exit of the FEL across the optics to the experiment. The input fields for the propagation were generated using the Genesis1.3 code. This work is part of collaboration in the IRUVX-PP consortium.

INTRODUCTION

A major challenge in reaching micron or sub-micron focal spot sizes using highly coherent short wavelength sources such as UV and X-ray FELs, is manufacturing mirrors with sufficiently high quality surfaces. In some cases, the focal spot size is mainly determined by the spread due to the mirror slope error.

Wavefront propagation is required to model the effect of surface imperfections on the radiation. A new wavefront code, FOCUS [1], was written at Daresbury Laboratory especially to look at such problems. The code represents any optical surface and the radiation field on the surface by their values on a grid of points, hence any mirror profile can be read-in, assuming that the grids required to adequately represent the surface and fields are not too large. In particular, measured surface profiles can be input into the code.

The beamline to be modelled is represented by a set of surfaces, and the very simple approach of propagating the wavefront from every point on a surface to each point on the next surface, using the Somerfeld Propagation intregral, is adopted. The numerical approximations are kept to a minimum so that the code is applicable to as wide a range of surface shapes and incident angles as possible. The code is designed to easily interface to other programs, in particular the PHASE wavefront code [2,3] and the FEL simulation code Genesis1.3 [4].

The simulations reported here pertain to beamline 3 on FLASH, the free electron laser at DESY.

NUMERICAL SIMULATIONS FOR BL3 AT FLASH

Input Radiation Field

The radiation field at the end of the FLASH FEL has been calculated using Genesis1.3, for an electron bunch of charge 0.5 nC and energy 689 MeV. The output pulse of radiation at an energy of around 93 eV is represented by 1230 'time slices', each of 151 * 151 points. The longitudinal beam properties have been modelled based on start-to-end simulations as presented in reference [5]. The parameters have been smoothed in order to suppress noise and obtain them at the desired electron beam energy of 689 MeV. Only the part of the bunch with a peak current exceeding 200 A has been included in the Genesis simulation.

The temporal intensity profile and beam cross-section are shown in Figs. 1 and 2. The rms beam size is 84 * 73 μm^2.

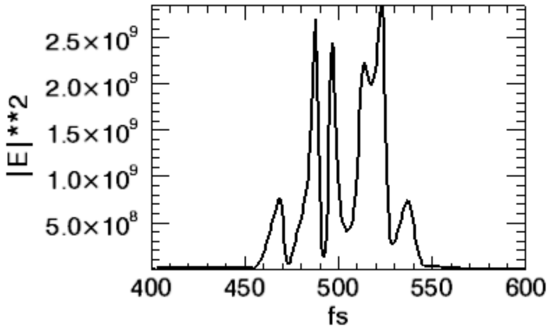

Figure 1: Input field intensity as a function of time summed over all pixels.

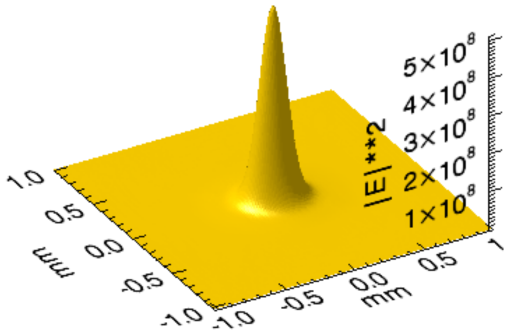

Figure 2: Transverse intensity distribution, summed over time.

The temporal profiles at each point on the transverse grid were Fourier transformed to obtain the spectra at each position. The fields for each photon energy were then propagated down the beamline. An inverse transform can be performed after propagation to reconstruct the pulse.

Mirror Profiles

Metrology data from the BESSY-NOM at the Helmholtz Zentrum Berlin [6] were available for two mirrors, made by Carl Zeiss, which will be installed on beamline 3 at FLASH.

The first is a 510 mm long state-of-the-art carbon coated plane mirror which was measured along its centre line to have a radius of 816 km and residual slope error of 0.074 arcsec (0.36 μrad). Only the central 300 mm was required for the wavefront propagation simulations.

The second is a 500 mm long ellipsoidal mirror; the specified and measured parameters of the ellipse along its central line are given in Table 1 (a and b are the semi-major and semi-minor axes of the ellipse and X_0 is the position of the mirror pole projected onto the major axis). The measured residual slope error in the middle 300 mm of the mirror is about 1.6 μrad, the slope error for the full 500 mm length is 3.6 μrad.

Table 1: Parameters for the Ellipsoidal Mirror

	a (mm)	b (mm)	X_0 (mm)
specified	37100.000	628.9031	35105.0442
measured	37099.8709	627.0124	35104.9776

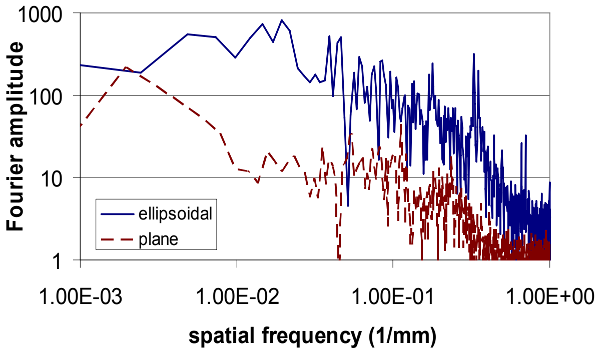

Figure 3: Comparison of the amplitude of the FT of the slope slope errors for the plane ellipsoidal mirror.

A comparison of the Fourier Transform of the slope errors for both mirrors is given in Fig. 3, where it can be seen that imperfections of wavelengths of 10's to 100 mm are more important for the ellipsoidal mirror. Note that the residual slope errors were calculated for a slightly different fit to the ellipse which will affect the values at the longest wavelengths.

The surface for the plane mirror used in the wavefront calculation was constructed by using the measured height on the centre line for all transverse positions. For the ellipsoidal mirror, a perfect ellipse using the fitted parameters was generated, and the deviation of the measured surface height from the perfect ellipse was used for all transverse positions, i.e the transverse slope error is set to zero for both mirrors. The deviation of the profile measured along the centre line of the mirror surface from the fitted ellipse as a function of longitudinal position is shown in Fig. 4 for the central 300 mm of the mirror.

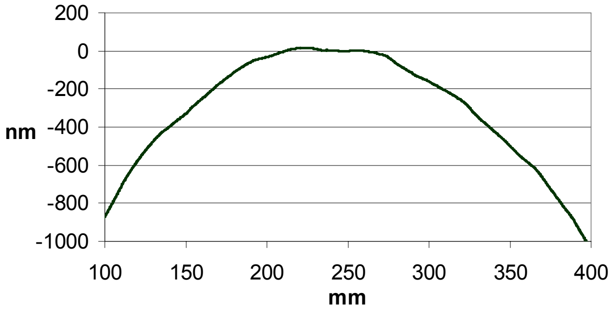

Figure 4: Deviation of the measured profile from a perfect ellipse.

Simulations

Beamline 3 at FLASH consists of 3 optics; 2 plane mirrors at 48 m and 52 m from the end of the FEL, with incidence angles of 2°, and an ellipsoidal mirror 72 m from the FEL, incidence angle 3°, focussing the FEL radiation at 2 m beyond the mirror. Using perfect optics, an image of the source of rms size 2.2 by 2.0 μm^2 is produced, consistent with a 37.5 times demagnified image of the input field.

In the first set of simulations, the imperfect plane mirror, as described above, was placed at 48 m from the FEL and its effect on the focus of a perfect ellipsoidal mirror was investigated. As the calculations are time consuming, the second plane mirror at 52 m from the FEL was omitted. In the second set of simulations, which looked at the effect on the focus caused by imperfections of the ellipsoidal mirror, only the ellipsoidal mirror was included, as it was found that the slope error of the plane mirror had very little effect on the focus.

RESULTS

Imperfect Plane Mirror

The radiation field at a single photon energy was propagated from the source to the first plane mirror, then to a perfect ellipsoidal mirror and finally to its focus. It was found that for this wavelength range, the surface of the plane mirror was of such a high quality that no effect from the surface imperfections on the focus of the ellipse could be seen (Fig.5). When the deviations were multiplied by a factor 5, a very slight difference could be observed in the beam cross-section, but the width of the focal spot was not affected. Multiplying the height deviations by 25, a break-up of the focus could be seen, due to the longer wavelength imperfections in the mirror surface (Fig. 6).

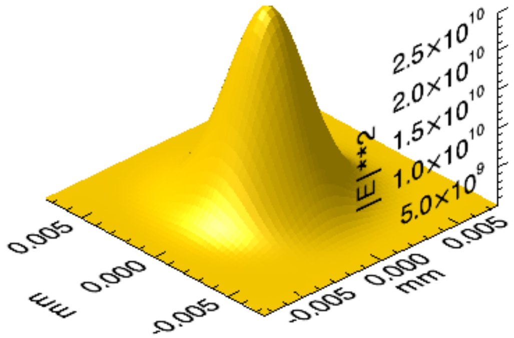

Figure 5: Square of the radiation field at the focus of perfect ellipsoid, with measured surface deviations added to the plane mirror M1.

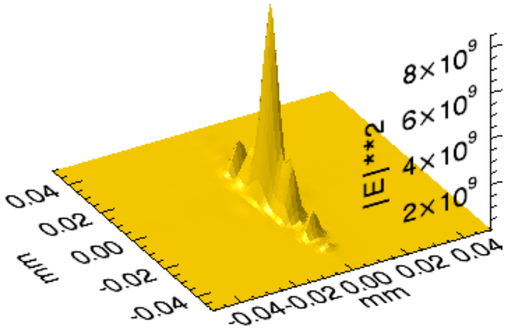

Figure 6: Square of the radiation field at the focus of perfect ellipsoid, with 25 times the measured surface deviations added to M1.

Imperfect Ellipsoidal Mirror

For the propagation, in order to get the best possible focus, the mirror and image plane were placed at the foci of the ellipse generated by the fit to the real mirror profile. Note however, these positions are shifted from the specified mirror foci by less than 200 µm. The beam cross-section at the focal plane for a single photon energy of 92.82 eV is shown in Fig. 7 and a cut through the focus is given in Fig. 8. The break-up of the focus into separate peaks, caused by long wavelength deviations in the mirror surface is seen. A Gaussian fit to the longitudinal cut through the centre of the main peak has an rms width of 2.0 * 4.0 μm^2 and the maximum intensity has fallen by about a factor 3 from the case using a perfect ellipse.

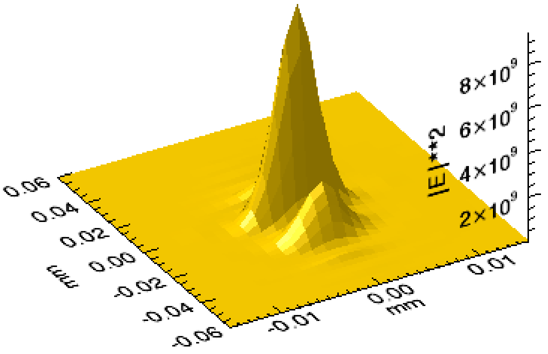

Figure 7: Square of the radiation field at the focus of imperfect ellipsoid.

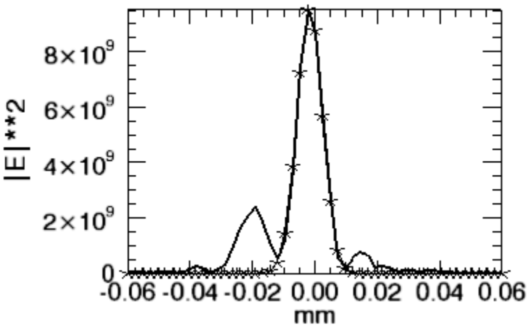

Figure 8: Longitudinal cut through the focus of the elliptical mirror. The * show a Gaussian fit to the central peak.

Effect on the Temporal Profile

The radiation fields for about 180 different photon energies were propagated across the ellipsoidal mirror and the pulse reconstructed at the focus. Comparing the input and output pulses, shown in Figs 1 and 9 respectively, it is seen that, as expected, the longitudinal pulse shape has not changed. The same result was found for the simulations using the plane mirror. The pulse shape varies slightly at different positions in the cross-section of the beam as is shown in Fig. 10 where the temporal profiles of the magnitude of the field are given for the point of maximum intensity and at the secondary peak.

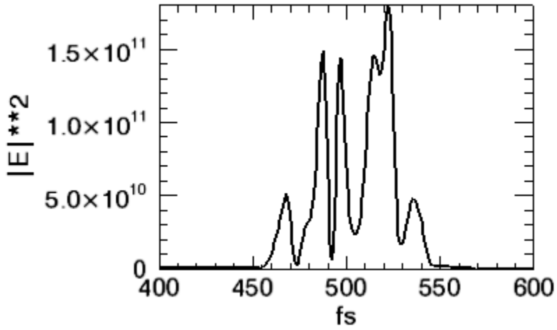

Figure 9: The temporal profile of $|E|^2$, summed over all pixels, at the focus of the ellipsoidal mirror.

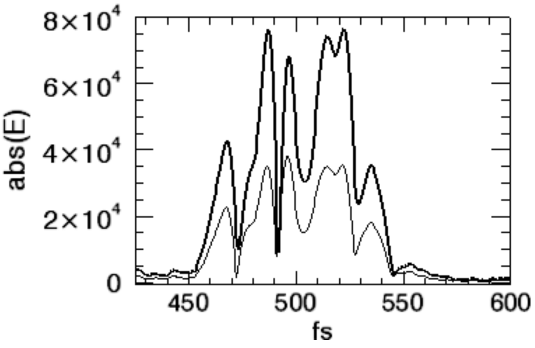

Figure 10: The temporal profiles of the field at the top of the main peak (thick line) and the subsidiary peak (thin line).

SUMMARY

The effects of realistic mirror imperfections on the radiation delivered to an experiment on a FEL beamline have been investigated. This forms another link in the chain of start-to-end simulations for FELs; metrology measurements of the beamline mirrors as well as radiation fields from detailed numerical calculations of the electron bunch transport and the FEL process were input into the simulations of the radiation propagation.

REFERENCES

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