
29th International
Free Electron Laser
Conference
FEL07
Budker INP, Novosibirsk
Aug 26-31, 2007
http://ssrc.inp.nsk.su/FEL07/

MODELLING MIRROR ABERRATIONS IN FEL OSCILLATORS USING OPC

P.J.M. van der Slot*, J.G. Karssenberg, K.J. Boller
Mesa+ Institute for Nanotechnology, University of Twente, Enschede, NL

Abstract

Several high power free-electron lasers (FELs) are currently under design, operational or being upgraded. One central issue is the beam outcoupling and mirror deformation due to absorbed power. Here we present an extension to the OPC code that allows it to model mirror distorions. We use this code to model the high average power vacuum ultra violet FEL oscillator of the 4th generation light source. Both Genesis 1.3 and Medusa are used to calculate the gain provided by the undulator. Our findings indicate that the high gain oscillator is quite resilient to thermal mirror deformation and operation well into the kW range of average power can be expected.

INTRODUCTION

Several high average power Free-Electron Lasers (FELs) are currently operational [1, 2] or planned [3]. One of the issues in these devices is the thermal distortion of the mirrors that can alter the optical mode and degrade performance. Including this and other mirror distortions in simulation of these devices is important to understand and further improve these devices. Several attempts have already been made to model thermal mirror distortions [4, 5, 6, 7], however, a full integration of the FEL gain medium, optical propagation in the non-amplifying section and mirror distortions for both steady state and time dependent simulations is not readily available. Here we present an extension to the OPC package [8] that allows it to model mirror distortions. OPC implements paraxial optical propagation in the non-amplifying sections of a resonator, while either Genesis 1.3 [9] or Medusa [10] is used to simulate the gain provided by the undulator.

It is well know that various mirror distortions can be described using the circle polynomials of Zernike [11]. Within OPC these polynomials are used to calculated a phase difference $d\theta$ according to

$$d\theta = A_{nm} R_n^{|m|}(\rho) \times \begin{cases} cos(m\phi) & m \geq 0 \\ sin(m\phi) & m < 0 \end{cases} \qquad (1)$$

where $R_n^{|m|}$ is the circle polynomial of order (n,m), ρ is the scaled radial distance $\sqrt{x^2+y^2}/\rho_c$, ρ_c being a characteristic distance, ϕ is the angle $\tan^{-1}(y/x)$, and A_{nm} is the amplitude of the aberration. These aberrations define a phase mask that is applied to the optical field at the position of the corresponding optical component. The scaling constants A_{nm} and ρ_c can either be kept constant or made dependent on certain properties of the optical field, e.g., the total power or the root-mean-square (rms) width of the optical beam.

Different type of aberrations can be modeled using Zernike polynomials. For example, $n = 4$ and $m = 0$ corresponds to spherical aberration, $n = 3$ and $m = 1$ to coma and $n = 2$ and $m = 2$ to astigmatism [11]. A combination of Zernike polynomials can also be used to model a cylindrical lens. Here we focus on the the use of Zernike polynomials to model thermal mirror distortions [6, 4].

As an example of a high average power FEL we consider here the vacuum ultra violet FEL (VUV-FEL) oscillator that is part of the 4th generation light source (4GLS) project of Daresbury laboratory [3]. This high gain oscillator uses a low Q cavity to generate coherent output with photon energies in the range 3 to 10 eV. The VUV-FEL will operate in the 600 MeV high average current branch of the energy-recovery linac, and is driven by ~ 80 pC electron bunches at multiples of $4\frac{1}{3}$ MHz up to a maximum of 1.3 GHz. A system of distributed bunch compression along the beam line is expected to compress the bunch to lengths as short as 100 fs, generating a peak current of ~ 300 A before injection into the VUV-FEL. The main system parameters used in the simulations are given in table 1. Since the average output power will be of the order of 300 W or multiples thereof, and the mirror only reflects 60 % of the radiation falling on the surface, significant mirror heating is expected.

We will first briefly discuss the mirror thermal expansion and the resulting phase distortion. We then continue with a simulation of the VUV-FEL with and without the mirror expansion included.

MIRROR EXPANSION UNDER A THERMAL LOAD

The mirrors considered for the VUV-FEL oscillator consist of a protected aluminium coating on a silicon substrate. The reflectivity R of the mirror is expected to be 60 % [3]. Radiation is extracted at the downstream (DS) mirror through a hole with a radius of $r_h = 1.8$ mm. We approximate the mirror loading in the form of a train of optical pulses by an average power and determine the steady state displacement $\delta z(r)$ of the reflecting mirror surface under the assumption that the average absorbed power P_{abs} will have a Gaussian profile with rms width σ_m.

We use the finite element program MultiPhysics with the Structural Mechanics Module [12] to calculate the temper-

* p.j.m.vanderslot@tnw.utwente.nl

Table 1: Baseline VUV-FEL parameters as used in the simulations.

Undulator	
Undulator period λ_u	58 mm
Undulator parameter K (rms)	1.9799
Periods per module	52
Number of modules	3
Electron Beam	
Electron beam energy	549.3 MeV
Relative energy spread (rms)	0.1 %
Bunch charge	80 pC
Peak current	300 A
Normalised emittance	2 mm-mrad
Optical Cavity	
Wavelength λ	123.89 nm
Cavity length L_{cav}	34.618067 m
Upstream ROC r_1	14.5 m
Downstream ROC r_2	21.7573 m
Mirror reflectivity R	60 %
Rayleigh length z_r	3.67 m
Fundamental mode waist w_0	0.38 mm
Waist position (from US mirror)	13.5 m
Outcoupling hole radius r_h	1.8 mm
Cavity stability $g_1 \times g_2$	0.82

ature distribution and the resulting surface displacement, δz. The DS mirror considered here has an outer diameter of 20 mm and a thickness of 10 mm. The thermal conductivity and thermal expansion are taken to be 1.2 W/cmK and 2.8×10^{-6} K^{-1} respectively. Although taken constant here, these can be allowed to vary with temperature. A heat flux with a Gaussian profile having a rms width σ_m and total flux of αP_o is used to load the reflecting surface of the mirror, where α is the absorption coefficient and P_o is the average optical power incident on the mirror. Note that only the fraction with $r > r_h$ will be absorbed by the mirror. The mirror is cooled at the outer edge, where we assume a heat transfer coefficient $h_T = 1000$ W/m^{2}K to a thermal sink that is kept at 293 K. The heat transfer coefficient of the backside of the mirror is set to $h_T/1000$. Mechanically, the mirror is considered to be mounted stress free with the reflecting surface pushed against a stable reference plane. Hence, the outer edge of the reflecting surface can only move radially. The rest of the mirror is allowed to expand freely. Taking the spot size of the heat flux on the mirror equal to the rms size of the optical beam found for the VUV-FEL in stationary state without mirror distortions, and using $P_o = 300$ W, $\alpha = 0.4$, we find that P_{abs} and σ_m are 35.3 W and 2.3 mm respectively for $r_h = 1.8$ mm. For these numbers, the temperature profile, $T(r)$, and mirror displacement, $\delta z(r/2\sigma_m)$ are shown in figure 1. For comparison, the profiles for the case $r_h = 2$ mm are also included. In this figure 1B δz is shown as a function of the

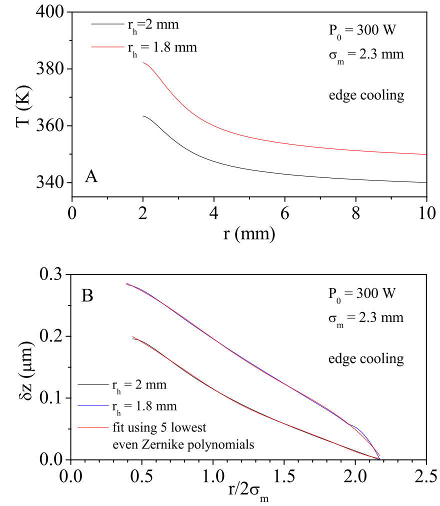

Figure 1: Temperature profile (A) and surface displacement (B) of the mirror for $P_{abs} = 35.3$ W ($r_h = 1.8$ mm) and $P_{abs} = 25.5$ W ($r_h = 2.0$ mm). Here $P_o = 300$ W and $\sigma_m = 2.3$ mm.

Table 2: Fit parameters for Zernike polynomials for the parameters of figure 1. The resulting δz is in [m].

	$r_h = 1.8$ mm	$r_h = 2.0$ mm
A_{00}	2.446e-7	1.639e-7
A_{20}	-5.544e-8	-5.641e-8
A_{40}	5.480e-9	8.037e-9
A_{60}	-2.9344e-10	-6.050e-10
A_{80}	3.773e-12	1.648e-11

scaled variable $r/2\sigma_m$, along with a fit to δz using Zernike polynomials:

$$\delta z(r/2\sigma_m) = \sum_{n=0}^{n=8} A_{n0} R_n^0(r/2\sigma_m) \tag{2}$$

where n only takes on even values. Figure 1 shows that the difference between the calculated displacement and the fit is far below $\lambda/10$. The fitting coefficients are given in table 2 for both $r_h = 1.8$ mm and 2 mm. To convert the surface displacement to a phase change we use

$$d\theta(r/2\sigma_m) = -\frac{4\pi\delta z(r/2\sigma_m)}{\lambda} \tag{3}$$

Since the phase shift is proportional to twice the surface displacement and the minus sign has to be chosen to be in agreement with the phase advancement used in OPC.

VUV-FEL OSCILLATOR WITH MIRROR DISTORTION

OPC is set up to use the fitting coefficients of table 2 to calculate the mirror displacement and then convert it to a phase mask using eq. 3. This phase mask is then applied to the DS mirror. As long as the spot size of the optical beam on the mirror does not significantly change, we do not need to recalculate the temperature and displacement profile. The amplitude of the phase shift can then be found by multiplying $\delta z(r)$ with the ratio $P_{abs}(t)/P_{abs,0}$ where $P_{abs}(t)$ is the instantaneous average power absorbed by the mirror and $P_{abs,0}$ is the absorbed power used to calculate the thermal expansion $\delta z(r)$.

One problem with modeling the mirror's thermal deformation is the difference between the time scale for the oscillator to reach saturation and the mirror to reach a stable thermal profile. The latter is determined by the thermal relaxation time, which is estimated to be of the order of 1 s for the DS mirror. On the other hand, the roundtrip time for the cavity is about 230 ns and the laser reaches steady state after about 20 roundtrips (~ 4.6 μs). Ideally, one would want to apply the absorbed energy of a single optical pulse to the mirror, and use a time dependent analysis to determine $T(r)$ and $\delta z(r)$ at the arrival time of the next optical pulse. The build up of the radiation and the thermal distortion would then be determined iteratively until a steady state was obtained. Although such a simulation can be set up with OPC using an appropriate finite element solver,this requires considerable computational resources and we have choosen to demonstrate the effect of thermal mirror distortions in a different way.

In view of the short time the VUV oscillator requires to produce a stationary output, we first let the oscillator reach this state and then apply the full thermal distortion instantaneously at the DS mirror and observe how the laser reacts. Although this ignors the temporal development of the distortions it gives a first impression of how the distortions affect the laser. Figure 2 shows the total power in and cross section of the optical field at various places along the resonator and in the far field (power only) after $n = 25$ and 50 roundtrips. The mirror distortion is applied after 30 roundtrips. Here Genesis 1.3 is used in steady state mode to propagate the optical field through the undulator and $f_{rep} = 4\frac{1}{3}$ MHz. It is clear that at these power levels the laser quickly adapts to the distortions in the phase front of the optical field without seriously affecting the power in the field. We do observe that the surface expansion focusses the field more towards the upstream (US) mirror and hence the spot size on this mirror is decreased and the intensity increased (about a factor of 2 on axis). The profile has changed as well and the intensity is now maximum on axis. Figure 3 shows the cross section of the field at the undulator's entrance as a function of the roundtrip. This figure shows that only a few roundtrips are required for the laser to adapt to the full mirror distortion.

The thermal load on the mirror increases when f_{rep} is increased. Figures 4 and 5 show the same data but now for $f_{rep} = 21\frac{2}{3}$ MHz. Again, the profiles at $n = 25$ are equal to the ones shown in figure 2B. Figure 4 shows that when the distortions are applied, the total output power at the undulator's exit drops by almost a factor of 50. Still, after about 10 roundtrips the laser finds a new equilibrium, albeit at an output level that is 70 % of the power without mirror distortions. Although a realistic model of the temporal behaviour of the mirror's thermal distortion is not used, these results indicate that an average optical output power of the order of several kW is feasible. This can still be further improved if the mirror can be cooled more efficiently.

OPC can also use Medusa [10] to calculate the gain and we have also simulated the VUV-FEL oscillator using this code. As Genesis 1.3 can not start from noise in steady

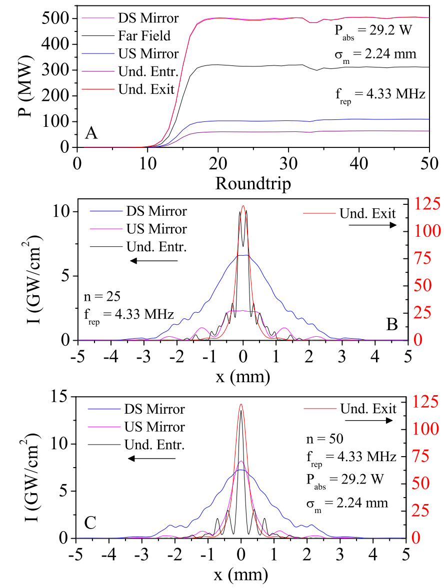

Figure 2: Total power as a function of roundtrip (A) and cross section of the field at various places in the cavity for $n = 25$ (B) and $n = 50$ (C). $f_{rep} = 4\frac{1}{3}$ MHz.

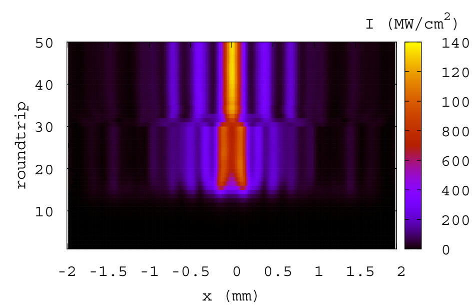

Figure 3: Cross section of the optical field at the undulator's entrance as a function of the roundtrip n. The thermal distortion is applied at $n = 31$ and $f_{rep} = 4\frac{1}{3}$ MHz.

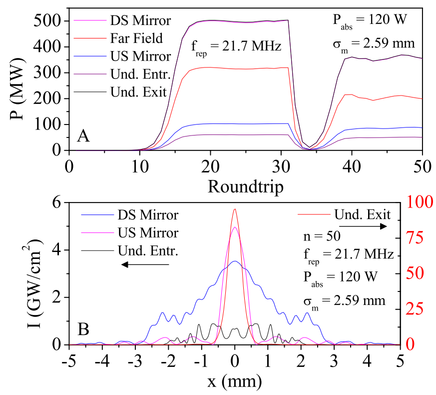

Figure 4: Total power as a function of roundtrip (A) and cross section of the field at various places in the cavity for $n = 50$ (B). $f_{rep} = 21\frac{2}{3}$ MHz.

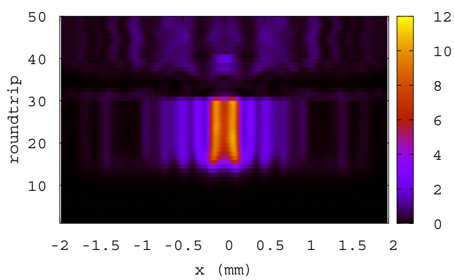

Figure 5: Cross section of the optical field at the undulator's entrance as a function of the roundtrip n. The thermal distortion is applied at $n = 31$ and $f_{rep} = 21\frac{2}{3}$ MHz.

state mode, both codes used a seed power of 2 W based on Ming Xie's formula for shot noise [13]. Preliminary results indicate that Medusa shows less optical guiding in the undulator during start-up. It predicts a larger spot size for the optical beam at the undulator's exit and consequently, the spot size at the DS mirror is found to be smaller. The feedback is then too small for the laser to start. Medusa can also start from noise in steady state mode. In this case, the field in the oscillator builds up and saturates at about 366 MW intracavity after about 40 passes without distortions. This is about double the number of roundtrips required by Genesis 1.3. Initial results with the mirror's thermal distortion turned on and using $f_{rep} = 4\frac{1}{3}$ MHz showed a similar behaviour. The differences found between Genesis 1.3 and Medusa are still under investigation.

DISCUSSION AND CONCLUSIONS

We have extended the OPC package to include mirror distortions using Zernike polynomials. These distortions are applied as a phase mask at the appropriate optical component in the resonator. Alternatively, the user may provide an external file that defines an arbitrary phase mask. OPC can easily be adjusted to interface with an apropriate time dependent finite element program that calculates the time dependent surface expansion resulting from a train of optical pulses incident on a mirror. Alternatively the instantaneous absorbed power based on the optical pulse energy and f_{rep} can be weighted with a thermal relaxation time that allows the mirror deformation to build up more slowly than the instantaneous average power. As an example we applied a simple implementaton of the thermal distortion by applying instantaneously the full distortion to the DS mirror of the 4GLS VUV-FEL oscillator after the oscillator has saturated. We used both Genesis 1.3 and Medusa for the gain calculation and there are some some differences in their predictions related to the startup of the laser that are currently under investigation. Nevertheless the case considered here shows that the laser is expected to be quite resilient to the mirror's thermal distortion.

ACKNOWLEDGEMENT

We would like to thank David Dunning, Brian McNeil and Neil Thompson of the 4GLS design team for the useful discussions, and Henry Freund and Buff Miner of SAIC for the Medusa simulations and discussions.

REFERENCES

[1] G. Neil, et. al., Nucl. Instrum. Methods Phys. Res. A**557** 9 (2006).

[2] E.J. Minehara, Nucl. Instrum. Methods Phys. Res. A**557** 16 (2006).

[3] B.W.J. McNeil, et. al., New J. Phys. **9** (2007) 239.

[4] S.V. Benson, et.al., Nucl. Instrum. Methods Phys. Res. A**407**, 401 (1998).

[5] A.R.B. de Castro, and T. Möller, Rev. Sci. Instrum, **76**, 063104 (2005).

[6] J.C. Goldstein, B.D. McVey, and B.E. Newman, Nucl. Instrum. Methods Phys. Res. A**296**, 288 (1990).

[7] H.P. Freund, M. Shinn, and S.V. Benson, *Proceedings 28th Free-Electron Laser Conference*, FEL'06, Berlin, Germany, Aug. 2006, p. 444, http://www.JaCoW.org

[8] J.G. Karssenberg, et.al., J. Appl. Phys. **100**, 093106 (2006).

[9] S. Reige, Nucl. Instrum. Methods Phys. Res. A**429**, 243 (1999)

[10] H.P. Freund, S.G. Biedron, and S.V. Milton. IEEE J. Quantum Electron. **36**, 275 (2000).

[11] M. Born and E. Wolf. *Principles of Optics*, 6th edition. Pergamon Press, 1980.

[12] Comsol Multiphysics V3.3a and Stuctural Mechanics module are from Comsol AB, Stockholm, Sweden. http://www.comsol.com

[13] M. Xie. Nucl. Instrum. Methods Phys. Res., A**445**, 59 (2000).