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SIMULATION OF OPTICAL TRANSPORT BEAMLINES FOR HIGH-QUALITY OPTICAL BEAMS FOR ACCELERATOR APPLICATIONS*

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Abstract

High-quality optical beams play already an important role in the field of particle accelerators which will most probably become even more prominent in the view of laser-driven particle accelerators. Nowadays, optical transport beamlines are needed for particle generation in photo injectors, for particle acceleration in laser-driven plasma wakefield accelerators, for particle beam diagnostics such as synchrotron radiation monitoring systems, or for particle manipulation schemes e.g. for external seeding of free-electron lasers. For the latter case, also the photon beam transport to the user end-stations requires dedicated optical beamlines. The utilized wavelengths range from the hard x-ray up to the far-infrared spectral range. Parameters such as surface quality, polarization effects, in- and out-of-vacuum damage thresholds, mechanical stability, dispersion effect, etc. need to be studied for the variety of applications. Here, we present the simulation results of the optical transport beamline for the seeding experiment at the free-electron laser FLASH and give a comparison to our measurement results.

INTRODUCTION

Designing optical systems for the application in particle accelerators needs to fulfill a variety of different demands. Especially the transport of high-quality laser beams for particle beam production or manipulation required detailed planning and quality control to achieve the desired properties. One example for the application of lasers in particle accelerators is the external seeding of free-electron lasers (FEL). The idea is to use the laser to manipulate the beam properties of an ultra-relativistic electron beam such that it efficiently generates very intense and fully coherent radiation pulses in the soft and hard x-ray spectral ranges. The interaction of the laser and the electron beam takes place in an undulator magnet which deflects the electron beam to an undulatory trajectory leading to a non-zero transverse velocity components. This, in turn, allows the interaction of the electrons with the electric field of the laser beam.

Seeding Experiment

Since 2010 an experimental setup for seeding has been installed at the FEL facility FLASH at DESY [1]. Initially installed for the investigation of direct FEL seeding [2] it also allows for the study of other schemes such as high-gain harmonic generation (HGHG) [3] or echo-enabled harmonic generation (EEHG) [4].

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SEED LASER INJECTION SYSTEM

The seed laser utilized in the seeding experiments at FLASH is a commercial, solid-state, Ti:sapphire system based on the chirped-pulse amplification technique (CPA) and consists of a mode-locked oscillator and a flash-lamp-pumped amplifier system (regenerative and booster) [5]. The system is capable of generating ultrashort laser pulses up to 50 mJ with 60 fs (FWHM) duration at a 10-Hz-repetition rate and a center wavelength of 800 nm. In 2012, a new laser transport beamline has been installed to inject ultraviolet (UV) laser pulses at a wavelength of 266 nm [6]. The generation of the UV pulses is done by frequency tripling (THG) of near-infrared Ti:sapphire laser pulses. Currently, the THG setup is located in the accelerator tunnel and placed under vacuum as shown in Figure 1. After UV generation, four mirrors (labeled M1 to M4) are used to steer the UV beam onto the electron beam axis without any refocusing of the UV beam. The longitudinal focus position is controlled by the NIR focusing into the THG setup. A half-wave plate allows for polarization control and a 1-mm-thick crystalline quartz window (QW) divides the ultra-high machine vacuum from the vacuum of the THG setup.

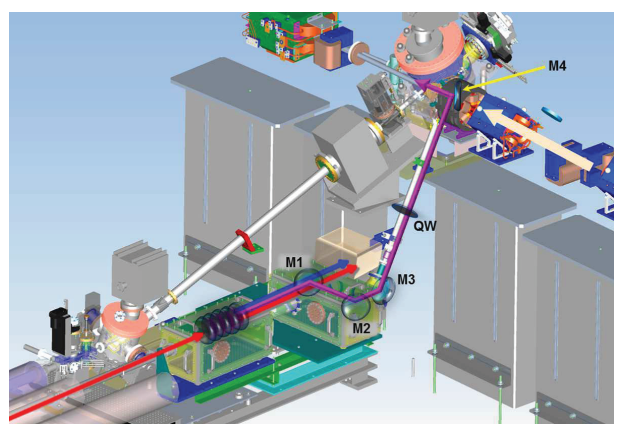

Figure 1: Seed laser injection setup. The NIR pulses arrive at the THG setup located in the accelerator tunnel inside high-vacuum chambers. The generated UV beam is steered with four mirrors onto the electron beam axis. The ultra-high vacuum of the machine is separated by a 1-mm-thick crystalline quartz window (QW).

Beam Polarization

For planar undulators, only the electric field component parallel to the deflection plane of the undulator couples to the electron beam. Therefore, the beam polarization of the

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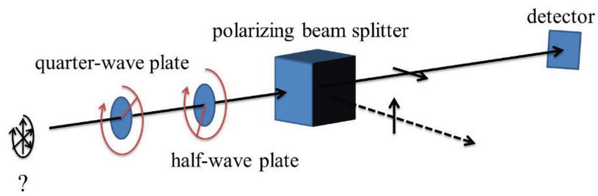

Figure 2: Schematic of polarimeter setup.

seed laser should be linear and being orientated in the wiggling plane of the electrons in order to maximize the effective energy transfer. The control of the seed beam polarization is simple in the case of seed wavelength where transmissive wave plates are available. Special care need to be taken, if the beam intensity gets too strong, e.g. due to small beam sizes or short pulse durations. Generally, a quarter-wave plate and a half-wave plate allow to change any polarization state to a linear polarization with the correct orientation. The UV beam polarization has been measured with a polarimeter consisting of a quarter-wave plate, a half-wave plate, a polarizing beam splitter and an energy meter as shown in Figure 2. The measurement results are presented in Figure 3. To extract the polarization state of the incoming beam for this measurement it is compared to simulation. Figure 4 shows the simulation results for an incoming beam with the following Jones vectors $J_x = 0.37 \cdot exp(1.4\,i)$ and $J_y = 0.93$. The corresponding stokes vector is $S = (1, -0.73, 0.12, -0.68)$.

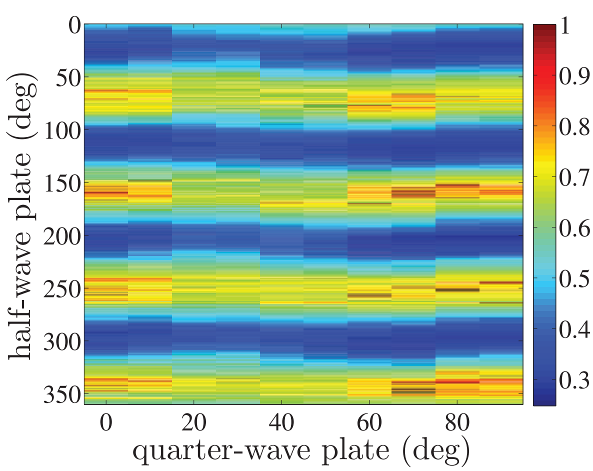

Figure 3: Measurement results with polarimeter setup.

MIRROR TOLERANCES

For design studies of seeded FELs the quality of the seed beam is often assumed to be ideal, namely the beam profile is Gaussian spatially and temporally. In reality, the seed beam and pulse properties are strongly depended on the quality of the optical components used for the beam transport. Here, we would like to concentrate on the surface quality, namely the flatness, of the mirrors used to transport the

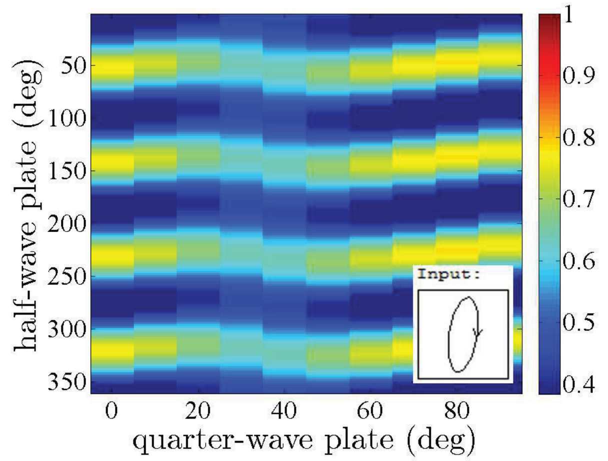

Figure 4: Simulation of polarimeter measurement. The inlet shows a representation of the polarization state given in the text.

seed beam into the interaction area. For the tolerance analysis, we are using the optics simulation software ZEMAX-EE [7].

Beam Quality

In laser physics, the figure of merit for the quality of a laser beam is the M^2-value [8], defined as the product of the beam waist size $W(0)$ times the far-field beam divergence $W(z)/z$, in analogy to the emittance in accelerator physics:

$$M^2 = \left(\frac{\pi}{\lambda z}\right) W(0) \cdot W(z) \text{ for } z \to \infty \tag{1}$$

The quality of the mirror surface will define the achievable laser beam quality at the interaction point with the electron beam. To determine the requirements of the seed beam quality for a seeded FEL numerical studies have been performed in the case of direct seeding [9] as well as for EEHG [10]. In the latter case, the tolerances on the laser wavefront distortions have been used as a measure for the beam quality. In order to translate the wavefront distortion into an M^2-value of the laser beam quality we performed the following simulations. The wavefront in the focus of a laser beam with a fixed waist size has been modulated using Zernike-polynomials up to the n-th order. The amplitude of the wavefront error has been set as an rms error $\sigma_{wavefront}$. We consider the cases with $\sigma_{wavefront} = \lambda/2, \lambda/4, \lambda/10, \lambda/20$, with λ being the seed wavelength of 266 nm. Table 1 shows the results of this simulation.

Table 1: M^2-values for Different Wavefront Distortions

	4th	6th	8th	10th
$\lambda/2$	5.2	5.3	6.7	7.0
$\lambda/4$	2.9	2.3	2.9	3.0
$\lambda/10$	1.3	1.4	1.4	1.5
$\lambda/20$	1.2	1.2	1.2	1.2

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Surface Flatness

Using the physical optics propagation and the tolerance capabilities of ZEMAX, we have setup the analysis as follows. The tolerance on the surface irregularities for each mirror is studied using standard Zernikes terms. We study the cases with all terms up to the 4th (14 terms), 6th (27 terms), and 8th (44 terms) order. Using an inverse limit analysis allows to set a maximum criterion for the cost function. Here, we use the M^2-value at the interaction region in the seeding undulator as the function of merit. Setting a certain limit, the software checks for each mirror the allowable mirror deformations. With theses values several Monte Carlo runs are performed. Table 2 shows the results for the best and worst Monte Carlo run for the different cases under study as well as the allowable mirror deformations for each mirror.

Table 2: Best case and worst case M^2-values for the different Monte Carlo runs and the respective allowable mirror deformation tolerances (rms) in nm

	4th	6th	8th
$M^2_{x/y}$ *best*	1.6/1.5	1.5/1.8	1.7/1.8
$M^2_{x/y}$ *worst*	1.6/4.3	6.2/2.3	4.2/2.3
flatness nm	13/13/20/18	9/10/7/12	6/7/2/9
$M^2_{x/y}$ *best*	1.6/1.7	1.6/2.1	1.7/2.1
$M^2_{x/y}$ *worst*	3.4/6.4	6.9/2.8	5.1/2.2
flatness nm	18/18/27/25	13/14/10/17	9/10/3/12
$M^2_{x/y}$ *best*	1.6/1.8	2.1/3.0	2.4/3.1
$M^2_{x/y}$ *worst*	4.5/7.7	11.2/3.5	10.3/2.9
flatness nm	24/24/38/33	18/18/17/22	12/13/6/16

In Figure 5 we show an example of the mirror deformations for mirror M1 considering Zernike polynomials up to the 8th order from one Monte Carlo run. For the same study case four simulated beam profiles with the respective M^2-values are shown in Figure 6.

The results of this analysis show, that for higher spatial frequencies of the deformation pattern, the tolerances on the rms flatness become more tight. Especially for mirror M3, the tolerances are far from what optics companies usually provide for optical laser applications. Also for the low order terms and for the most relax criterion, the tolerances on the mirror flatness is still between 25 and 40 nm. To get mirrors with that specification, companies typically offer mirrors with $\lambda/20$ surface flatness, where λ is 633 nm. As one can see, in the worst case the beam quality can degrade to M^2 values larger than 4, which would degrade the seeding efficiency by a factor of 2 according to [9].

SUMMARY

In this contribution, we presented simulation for the optical transport beamline for the seeding experiment at the free-electron laser facility FLASH. For FEL seeding, the

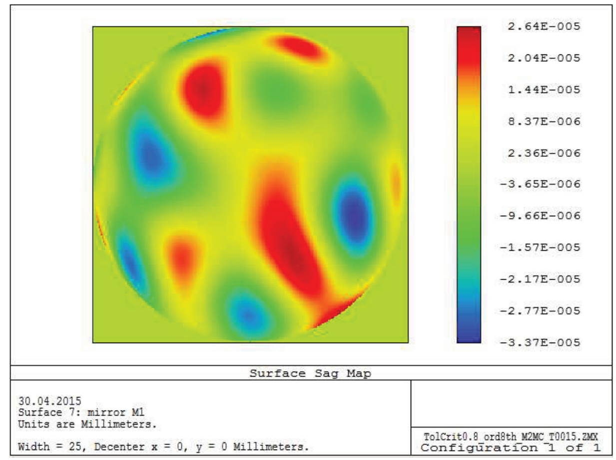

Figure 5: Example view of mirror M1 for one of the tolerance Monte Carlo runs considering Zernike terms up to the 8th order.

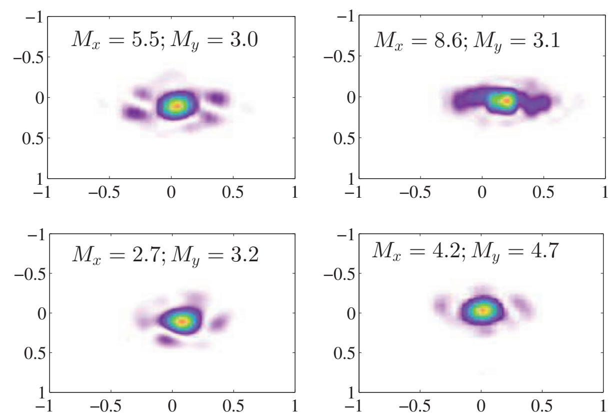

Figure 6: Example of four beam profiles at the beam waist position. Taken from Monte Carlo runs for Zernike terms up to the 8th order. The scale is in mm.

polarization of the seed beam as well as the beam quality are important parameters for an efficient energy transfer between seed laser and electron beam. The polarization of the UV seed beam has been measured with a polarimeter and the results were evaluated by comparison with simulation. A tolerance study for the flatness of the mirror surfaces for our particular beamline has been performed. The results show, that the required beam properties for seeding set tight tolerances on the surface quality of the mirrors which is at the edge of the available standards.

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