SOURCE CHARACTERIZATION OF THE BESSY SOFT X-RAY FEL*

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Abstract

BESSY proposes a soft X-ray free electron laser (FEL) multi-user facility [1]. It will consist of three undulator lines, each based on cascaded High-Gain Harmonic-Generation (HGHG) scheme delivering photons in the energy range of 24 eV to 1 keV. Start-to-end simulations including error sources from the injector, and linac structure have been performed to provide information about the expected radiation field [2]. However, the beamline designer needs to know the exact location and the size of the photon beam waist to maximize the brightness at the sample. These information can be obtained by the longitudinal propagation of the electric field distribution extracted from simulation results using the code GENESIS [3]. The results of the start-to-end simulations are used to predict the photon beam properties of the BESSY soft X-ray FEL.

INTRODUCTION

BESSY plans the construction of a linac-based seeded FEL multi-user facility. The FEL facility will consist of three undulator lines with three experimental stations each. The independent HGHG-FEL lines deliver reproducible ultra short pulses in the photon energy range of 24 eV to 1 keV with a peak-brilliance of about 10^{31} photons/sec/mm^2/mrad^2/0.1% BW. The polarization of the output radiation will be variable.

A photoinjector and a superconducting 2.3 GeV CW linac will feed the FEL lines. Each line will be seeded by a tunable laser. The seed is of Gaussian profile with a peak power of 500 MW, and a pulse duration of about 15 fs (rms). The High-Gain Harmonic-Generation scheme [4, 5] will be used to up-convert the seed frequency to the desired frequency range. In this scheme, the laser seed imprints an energy modulation onto the electron beam during the passage through an undulator (modulator). A dispersive section converts this energy modulation to an spatial modulation optimized for a particular harmonic. The following undulator is optimized for this harmonic and delivers high power radiation which seeds the next stage. The final amplifier, seeded at the desired wavelength, is brought to saturation.

In order to obtain as realistic as possible information about the properties of the FEL output, start-to-end simulations including error sources from the injector, and linac have been performed for the Low-Energy (LE) line of the BESSY FEL. Figure 1 shows spectral power averaged over the output of these simulations. Even including several error sources, the spectral output, i.e. the wavelength with the maximum power, of an HGHG-FEL is stable. For more details see ref. [2]

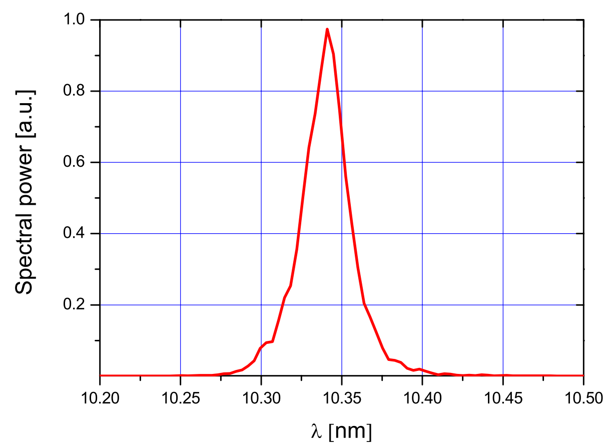

Figure 1: The average spectral power for the start-to-end simulations including error sources from injector and linac is shown.

GENESIS as well as other FEL-simulation codes calculate the development of the radiation field along the undulator. A virtual source point, i.e. the exact location and the size of a virtual radiation waist, is not determined by these codes. As the radiation size extracted from the GENESIS output at end of the FEL line is not the waist size, the calculated phase space volume turns out too large.

However, for an adequate design of the beam lines, the knowledge of the exact location and size of the photon beam waist is essential. The longitudinal propagation of the electric-field distribution of the FEL output delivers this information [6]. The electric field extracted from the results of the start-to-end simulations can be used to investigate how far the injector and linac errors affect the photon beam size and waist locations. As the output of the LE-FEL is rather stable, we decided to analyse only the cases which differ significantly from the nominal, reference, case. After introducing the examined cases and the calculation method briefly, the results are presented and the expected variation of the photon beam size and waist location is discussed.

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EXAMINED CASES AND CALCULATION METHOD

The criteria for the choice of the analysed cases were pulse duration, peak power, wavelength and bandwidth. They differ in at least one of these properties from the reference case. Figure 2 shows the power and spectral distributions of the reference bunch, and the chosen cases, named by their start-to-end bunch number.

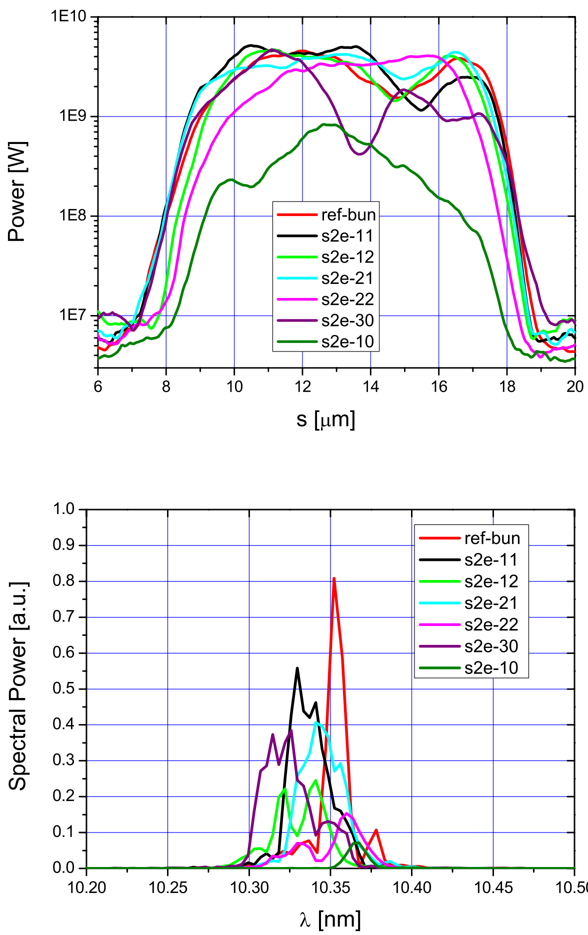


Figure 2: Power and spectral distribution of the reference bunch, and the examined cases, named by their start-to-end bunch number are shown.

The longitudinal propagation of the electric field distribution is performed using the Fourier optic method. An FFT yields the angle distribution of the FEL output:

$$\vec{E}_0(\nu_x,\nu_y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \vec{E}(x,y)\cdot e^{-2\pi i(v_x x + v_y y)} dx \cdot dy.$$

This distribution is multiplied by a factor which represents a longitudinal drift of Δz:

$$\vec{E}(\nu_x,\nu_y) = \vec{E}_0(\nu_x,\nu_y)\cdot e^{2\pi i \Delta z\sqrt{1/\lambda^2-\nu_x^2-\nu_y^2}}.$$

An inverse FFT provides the spatial distribution at $z = z_0 + \Delta z$:

$$\vec{E}(x',y') = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \vec{E}(\nu_x,\nu_y)\cdot e^{2\pi i(\nu_x x + \nu_y y)} d\nu_x \cdot d\nu_y.$$

GENESIS calculates the interaction of radiation field and electrons by dividing the electron bunch in slices. Each slice is as long as the radiation wavelength. For each slice, the transverse distribution of the electric field can be extracted. In order to decide how many slices are needed to provide reliable results using the Fourier optic method, calculations with different numbers of extracted slices wer performed for the reference bunch. Figure 3 shows a comparison between calculations with 20 and 400 slices. The electric field distribution of 20 slices describe the radiation field almost as good as 400 slices, as the waist sizes and locations for the both calculated cases are nearly identical.

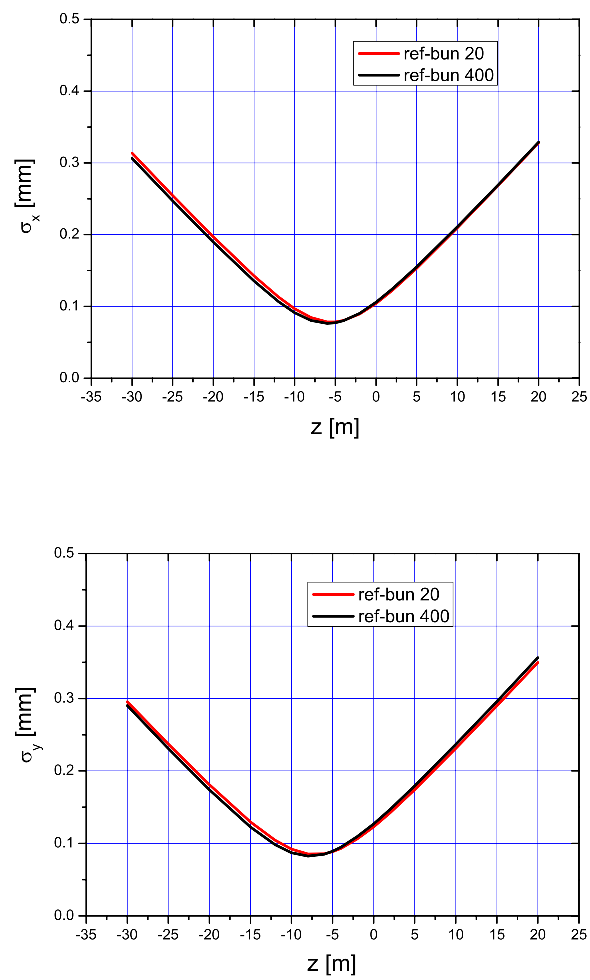
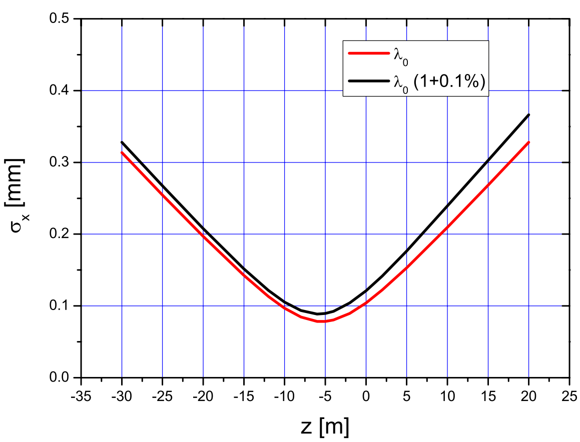


Figure 3: A comparison between calculations with 20 and 400 slices using the Fourier optic method. Using the electric field distribution of 20 slices describes the radiation field almost as good as using 400 slices.

For the calculations the corresponding electric fields are propagated in untis of Δz, with $-30\text{ m} \leq \Delta z \leq 20\text{ m}$, and the intensities are projected onto the horizontal and vertical plane. For the present studies, 20 slices of the interacting region are extracted to describe the electeric fileds. The calculations are performed at the frequency of maximum intensity. For the reference case, the fields for a frequency shifted by 0.1% have also been propagated. The results for main frequency and and the shifted frequeny are shown in figure 4. The waist size increases for the shifted frequency whereas the waist location remains.



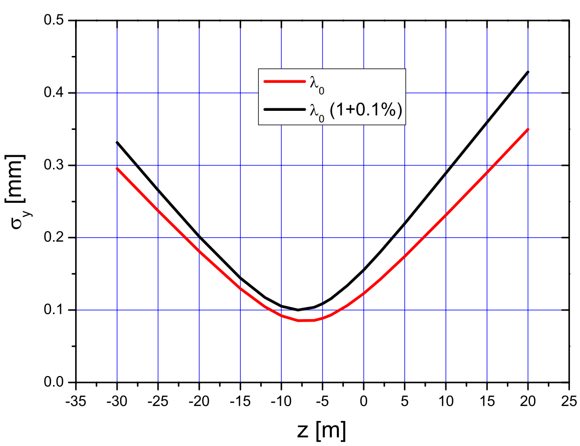
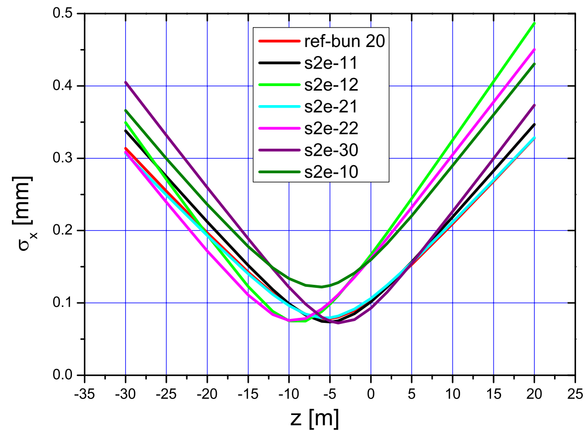


Figure 4: A comparison between calculations at the frequency of maximum intensity and a frequency 0.1% shifted is shown.

SIMULATION RESULTS

The exit of the FEL line is at $z = 0$. For the reference case the photon beam waist is located 5 m upstream, see figure 3. The rms-value of the horizontal and vertical waist amount to $\sigma_x = 0.078$ mm and $\sigma_y = 0.089$ mm. The horizontal and vertical waist positions do not coincide.



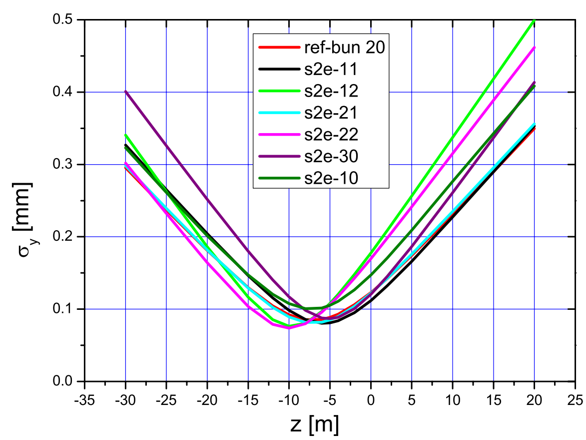


Figure 5: The horizontal and vertical waists of the examined cases are shown compared to the reference bunch. The deviation from the nominal beam size amounts to 56% horizontally and 13% vertically.

The horizontal and vertical waists calculated for the error cases are shown in figure 5. The location of the photon beam waist varies between -5 m and -10 m. The deviation from the nominal beam size rises up to 56% horizontally and 13% vertically. The horizontal and vertical waist position may differ up to 1 m for the same case.

For a diffraction limited photon beam with a wavelength of 10.364 nm the phase space volume is given by: $\sigma_r \cdot \sigma'_r = \lambda/2\pi = 1.65 \cdot 10^{-3}$ mm mrad, where the rms radiation size $\sigma_r = \sqrt{\sigma_x^2 + \sigma_y^2}$, and divergence, $\sigma'_r = \sqrt{\sigma'^2_x + \sigma'^2_y}$. For the reference case this product is about $2.07 \cdot 10^{-3}$ mm mrad which is close to the theoretical limit. The maximum deviation from the theoretical limit amounts to a factor of two for the examined cases. The phase space volume as a function of the waist location

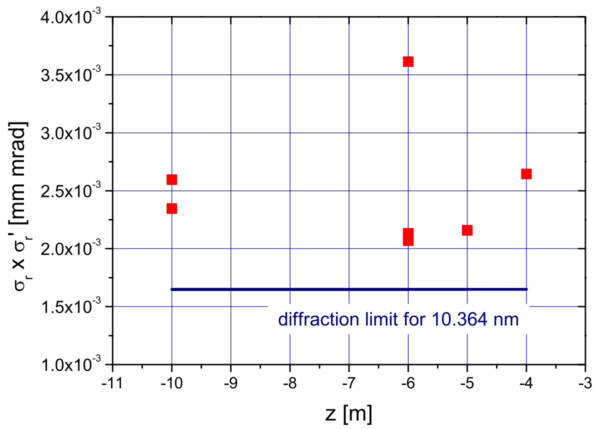


Figure 6: The phase space volume as a function of the waist location for the examined cases. The theoretical value for adiffraction limited photon beam is shown for comparison.

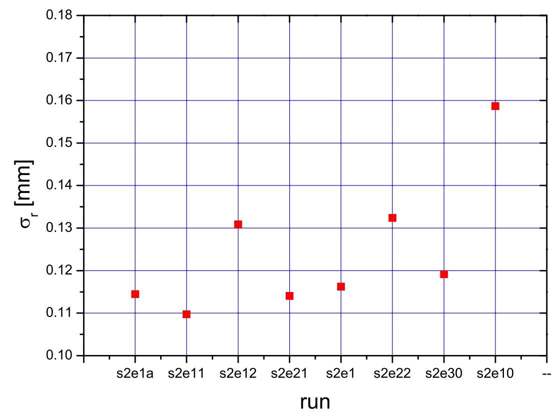


Figure 8: The transverse radiation size at the location $z = -6$ m for examined cases.

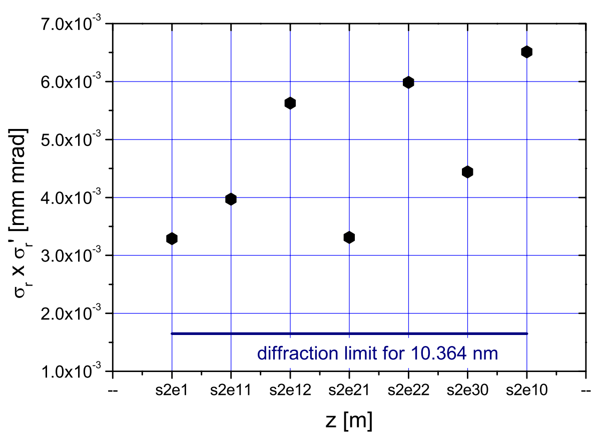


Figure 7: The phase space volume using the GENESIS output for the examined cases at the end of the final amplifier is shown. The phase space volumes are too large as expected.

is depicted in figure 6.

Figure 7 shows the phase space volumes calculated using the radiation size and divergence which are extracted directly from GENESIS output for the examined cases at $z = 0$. The maximum deviation from the theoretical value for a diffraction limited photon beam amounts to roughly a factor of four.

However, the brightness of the FEL radiation can suffer from the variations of the transverse size and the location of the photon beam waist which are caused by the injector and linac errors. For example, the virtual waist size at the position $z = -6$ m can vary between 0.11 mm and 0.16 mm from shot to shot, as shown in figure 8. This fact has to be regarded in the design of the beam lines.

CONCLUSION

The electric fields extracted from the results of the start-to-end simulations are used to investigate the influence of the injector and linac errors on the photon beam size and waist locations. The studies show an upper limit for the variation of the waist size and location, as they were performed for cases with output properties significantly different from the reference case. Due to the stabilising effect of HGHG scheme [2], these cases occur rarely. Although the reference case is close to the theoretical value of a diffraction limited photon beam, the phase space volumes of the examined error cases can be a factor of two larger than the theoretical limit. For an adquate beam line design the variation of the radiation size and the waist location due to the injector and linac errors has to be taken into account.

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