CHARACTERIZATION OF THE LASER BEAM FOR HHG SEEDING

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Abstract

Recently free-electron laser (FEL) facilities around the world have shown that the direct seeding approach can enhance the spectral, temporal and coherence properties of the emitted radiation as well as reducing the fluctuations in arrival time and output energy. To achieve this, a photon pulse of the desired wavelength ("seed") is overlapped transversely and temporally with the electrons in the undulator to start up the FEL process from a defined radiation pulse rather than from noise. To benefit from the advantages of this technique, the energy of the seed has to exceed the energy of the spontaneous emission. The ratio between these two energies is strongly influenced by the seed beam properties. In this contribution, we will present simulations on the achieveable power contrast in dependence on the beam quality of the seed, and compare the results to the experimental data of the seeded FEL experiment ("sFLASH") at DESY, Hamburg. Additionally we show a way of creating FEL seed pulses for simulation purposes from Hermite-Gaussian generating functions.

INTRODUCTION

In order to benefit from the advantages of the high-harmonic generation ('HHG') direct seeding approach one has to ensure good quality of the external photon pulse ('Seed') as the energy transfer between the electrons and the electromagnetic field is strongly depending on the photon pulse wave front properties [7], which is in principle accessible through measurement, for example using a Shack-Hartmann wavefront sensor [9]. In an FEL the direct measurement of the wavefront distortions in the vicinity of the undulator is challenging due to limited space, or even excluded, e.g. if the beam pipe is small [2]. The M^2 -value [1] can be easily measured by focus scan technique [11] in the laser lab. In this contribution, we present simulations showing the importance of the M^2 -value onto the FEL output power as well as a method for the estimation of the M^2 -value using modal decomposition of single transverse intensity profiles similar to [5]

NUMERICAL SIMULATION SETUP

These studies have been carried out using the time-dependent 3D FEL code "GENESIS 1.3, v2" [14]. The electron beam line considered in the simulations is similar to the FLASH2 beam line of the FEL facility FLASH at DESY, Hamburg, Germany [6], [8]. Table 1 contains all important simulation parameters.

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Table 1: Simulation Parameters and Ranges used in the Numerical Simulation

Electron beam		
Peak current	I_{max}	2.5 kA
Beam size	σ_{x}	100 μm
	σ_{y}	49 μm
Bunch Length (rms)	σ_{z}	30 μm
Energy	E	700 MeV
Energy spread	σ_{E}	500 keV
Normalized emittance	$\epsilon_{\mathrm{x,n}}$	1.4 mm · mrad
	$\epsilon_{\mathrm{y,n}}$	1.4 mm · mrad
HHG pulse		
Temporal shape		Gaussian
Wavelength	λ_{HHG}	37.6 nm
Pulse energy	E_{HHG}	70 pJ
Peak power	$P_{\mathrm{max,HHG}}$	2.5 kW
Duration (rms)	τ_{HHG}	12 fs
Undulators		
Lattice		FODO
Number of undulators		3
Undulator period	λ_{u}	31.4 mm
Periods per undulator	periods	76
Undulator intersection	L_{drift}	91.36 cm
Max. K parameter (rms)	K_{rms}	2.0

The goal of these simulations is to show the FEL output power at the end of the beam line as a function of the seed laser pulse quality in terms of M^2 . It has been assumed that the waist of the incoming seed pulse is located at the entrance of the first undulator module. For all simulations the waist size has been set to the value yielding the maximum FEL output power with an M^2 =1, namely 55 μm. Field distribution files containing seeds with different M^2 -values have been generated by superposition of different Hermite-Gaussian modes. The direct-search numerical algorithm [13] has been used to find amplitude and phase of the contributing modes to fullfill the following boundary conditions:

- The waist size has to be 55 μm.
- The total seed power equals 2.5 kW, see Table 1.
- M^2 is equal to the desired M^2 -value for **both** planes.
- In order to keep the axial symmetry of the multimode seed field, only TEM_{mn} modes with even *n,m* are considered.

A large number of sets of Hermite-Gaussian modes exist fulfilling the aforementioned boundary conditions - we

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pick the one consisting of the smallest possible number of higher order modes. This is implemented in the numerical algorithm, which starts with the fundamental mode and higher order modes are being added in steps of one to the field only if a solution with the desired M^2 could not be found.

FEL OUTPUT POWER VS. SEED PULSE M^2 -VALUE

The simulation results have been summarized in Figure 1 with the power contrast $\frac{P_{\text{pk}}-\langle P_{\text{SASE}}\rangle}{\langle P_{\text{SASE}}\rangle}$ as the figure of merit. P_{pk} stands for the peak output power for the seeded FEL, $\langle P_{\text{SASE}}\rangle$ for the SASE power time averaged over the FEL photon pulse. As expected, the contrast has a maximum

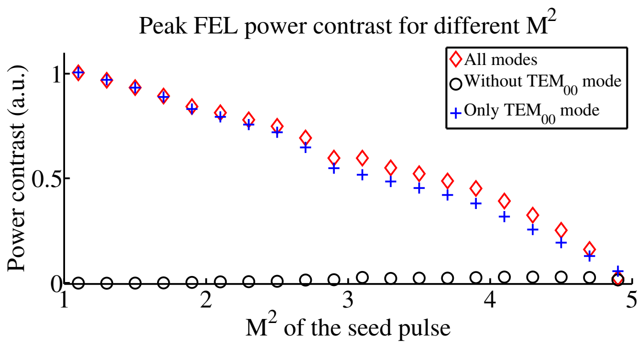

Figure 1: Seeded FEL power contrast vs. M^2 of the seed pulse.

at M^2 =1 with a maximum contrast of about 20 and drops rapidly to 0 at an M^2 of about 5. In order to give a proper interpretation of these results, all the higher order modes in the seed field distributions have been taken out except the fundamental. The simulations have been repeated and the results are plotted in Figure 1. The comparison between the seeding with the full modal content and the TEM_{00} only shows that mainly the fundamental mode contributes to the seeded FEL output power. One can say that the fundamental mode almost exclusively defines the reachable power contrast, while higher order modes do not seem to contribute anyhow. In order to support this conclusion, a simulation has been done using only the higher order modes. The results, also shown in Figure 1 show that FEL seeded with such fields have almost zero output contrast compared to SASE, meaning SASE is still the dominating radiation process. The drop in the FEL power contrast can be understood if one sees that the TEM_{00} mode size is reduced when the waist size is kept constant while higher order modes are added, leading to inefficient coupling between electron and the seed pulse. Additionally, since higher order modes require to carry some energy, less energy is avaible for the fundamental mode, decreasing the power contrast further. In the exponential growth regime, the FEL works as a linear amplifier, so that the characteristics of the plot should be independentfrom the longitudinal position inside the undulator as long as one stays in this mode. One has to not that in the simulation power contrast is the figure of interest, while for the photon users usually the energy contrast counts. The energy contrast can be estimated by scaling the power contrast ratio between SASE photonp pule length. In addition, this simulation allows to see the influence of the M^2 of the seed on the M^2 of the FEL. Out simulation gives an M^2 at the end of the FEL of 1.38 and independent from the initial M^2 . This means that the FEL does not benefit from seeding in terms of transverse photon beam quality.

MODAL RECONSTRUCTION OF INTENSITY PROFILES

Due to space restrictions in the vincinity of the undulator it is very challenging to measure the M^2 at the undulator, and therefore rarely done. M^2 is usually measured using the focus scan technique [11]. In [10] a different method is suggested to obtain M^2 -values from single transverse intensity profiles using decomposition into certain sets of modes. Provided that an observation screen is at the waist of the seed beam, this method can offer an estimate of the M^2 of the seed pulse and only requires little space. The field amplitudsme can be considered as superposition of Hermite-Gaussian functions [10], which in the one-dimensional case is:

$$G_n(x) = \left(\frac{2}{\pi}\right)^{\frac{1}{4}} \frac{1}{\sqrt{2^n n! w(z)}} H_n\left(\frac{\sqrt{2}x}{w(z)}\right) \exp\left(-\frac{x^2}{w^2(z)}\right) \tag{1}$$

The two dimensional approach has been derived in [15] where the two-dimensional intensity distribution in the waist is given by

$$I(x,y) = \sum_{n,n',m,m'=0}^{\infty} [A_{nm} G_n(x) G_m(y) \times A^*_{n'm'} G_{n'}(x) G_{m'}(y)] \tag{2}$$

Here one exploits the fact that the generalized Guoy phase (Eq. (5c) in [15]): is zero at the waist. Assuming that all modes are independent from each other, the time-averaged intensities can be added which means that the elements $A_{nm}A_{n'm'} = c_{nm}\delta_{nn'}\delta_{mm'}$ where δ_{mn} is the Kronecker symbol. The time-averaged intensity Eq. (2) can then be written as

$$\bar{I}(x,y) = \sum_{n,m=0}^{\infty} \left(c_{nm} G_n^2(x) G_m^2(y)\right) \tag{3}$$

where c_{nm} are the weights representing the intensity content of the individual modes. These coefficients can be calculated as shown in [10] using the Fourier transform $\tilde{I}(p_x,p_y)$ of the intensity distribution where p_x, p_y are the space-frequency variables.

$$c_{nm} = C_0 \int_0^{\infty}\int_0^{\infty} \left[\tilde{I}(p_x,p_y)\Psi_m(\pi^2 w_0^2 p_x^2) \times \Psi_n(\pi^2 w_0^2 p_y^2) p_x p_y \mathrm{d}p_x \mathrm{d}p_y\right] \tag{4}$$

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where $\Psi_n(t) = L_n(t)\exp\left(-\frac{t}{2}\right)$ with L_n the n-th order Laguerre polynomial. The constant C_0 is a normalization factor which is used to adjust the total power of the reconstructed field to the measured one. Although the method provides unique solutions for the power content coefficients, in practice one has to set an upper limit for the expected highest mode number. This means that the summation in Eq. (3) does not go to infinity but is limited to upper summation bounds $n_{\text{max}}, m_{\text{max}}$. In the following analysis of experimental data, we set a threshold where the reconstructed intensity profile yields more than 95% of the original intensity which was the case for $n_{\text{max}} = 8$. The upper bounds depend on the considered profile and has to be adjusted for each particular case. It is worth noting that the precise calculation of M^2 requires high number of modes as noted in [15]. However, the higher order modes tend to have very small intensities, close to the noise level of the detector, and therefore it is difficult to obtain a precise estimate for their power intensity coefficients from experimental data. From this point of view the choice of n_{max}, m_{max} is a compromise between the need to correctly measure M^2 and the desire to keep the measurement error small. These issues have been covered in the discussion on the measurement errors in the section below. In our analysis the waist size w_0 of the fundamental mode is a free parameter which can be fitted using maximum likelihood approach using the following numerical algorithm: One starts with some initial guess for w_0 and one computes the mode content coefficients c_{nm} where $n, m = 0...n_{\text{max}}$. Based on these coefficients, one calculates the intensity distribution $\hat{I}$ using Eq. (3). Further the algorithm adjusts w_0 until the difference $\left(\bar{I} - \hat{I}\right)^2$ reaches a minimum.

COMPARISON TO EXPERIMENTAL RESULTS

We have used this method to analyze the 38 nm HHG seed pulse at the sFLASH direct seeding experiment [12, 4]. The transverse intensity profile at the waist shown in Figure 2. As one can easily see, the intensity distribution is tilted and asymmetric. There are three possible sources for this [3].

- The first is the injection beam line which transports the seed pulse from the harmonics source to the undulators, which rotates the beam by about 11°, thus introducing coupling between x and y.
- Astigmatism out of the source, as experimentally studied in [12], is the second one.
- Third, the NIR laser beam used for the production of the harmonics is also already astigmatic, imprinting this property to the produced seed pulse.

All of these lead to odd modes contributing to the intensity distribution. Since in our analysis two-dimensional Fourier transform of the intensity distribution has been done, the decomposition algorithm is not restricted to even modes and can also be used to determine the modal content of arbitrary intensity profiles.

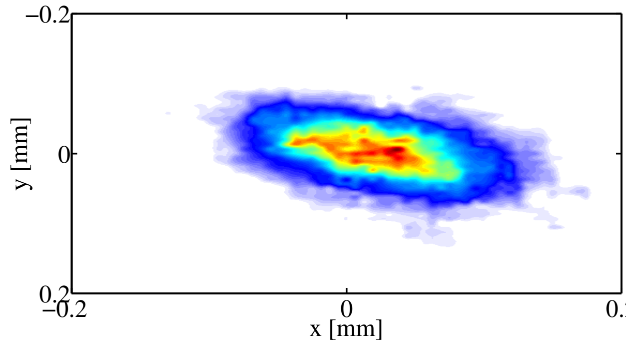

Figure 2: Transverse intensity distribution of the 38 nm HHG seed beam used at the direct seeding experiment sFLASH.

The power content coefficients which are the result of the modal decomposition, are shown in Figure 3. With this power coefficients one can calculate M^2 of the field. The first option is to use the formula derived in [15] which directly relates the beam quality factor to the power content coefficients:

$$M^2 = \frac{\sum\limits_{n,m=0}^{\infty} ((2m+1)c_{nm})}{\sum\limits_{n,m=0}^{\infty} c_{nm}} \tag{5}$$

Applying Eq. (5) yields $M_x^2 = 2.45$ and $M_y^2 = 2.39$. This result is in a very good agreement with the result obtained with the second possible option which is to numerically propagate the field over a certain distance and thus obtain the dependence of the beam size versus longitudinal position $w(z)$ and then analyze this date in the same way as a focus scan technique by exploiting the formula $M^2 = \frac{\pi w_0}{\lambda z}\sqrt{w^2(z) - w_0^2}$. One can estimate the M^2 of the HHG seed beam to be $M_x^2 = 2.2 \pm 0.6$ and $M_y^2 = 2.0 \pm 0.6$. The error of 28% consists of two contributions: Uncertainties in the determination of the wavelength and beam size due to finite camera pixel size where studied in Monte Carlo simulation yielding an error of about 20%. This Monte Carlo simulation works as follows: A random set of modes is generated and the corresponding intensity profile calculated, which is then transformed to a discrete distribution on a grid with the size of the camera pixels and a intensity resolution corresponding to the bit-depth of the camera. Noise is added afterwards. Then, the modal decomposition is applied. An uncertainty of 10% in the wavelength has been assumed, which is similiar for all pixels. This procedure has been repeated 10^5 times and the resulting values are plotted in Fig. 4. Another error to the measurement is introduced if the measurement has not been done directly at the waist position. This error source has been also studied by scanning the z-position. Within one Rayleigh length this leads to an error of 20% or less.

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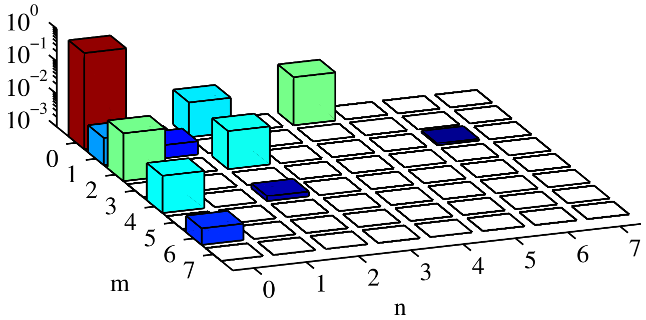

Figure 3: Power content coefficients c_{nm} of the harmonics beam shown in Fig. 2. The TEM_{00} mode is with around 90% of the overall intensity the strongest mode. Power content coefficients smaller than 10^{-3} are colored white.

Both errors may be summed up quadratically as they are independent of each other, leading to a error of about 28%. However, since the real waist size of the fundamental is unknown and one is not necessarily dealing with partially coherent beams, the calculated M^2 -value can only be a qualitative estimate although values calculated with this method are comparable to each other and within errorbars in good agreement with focus scan technique values.

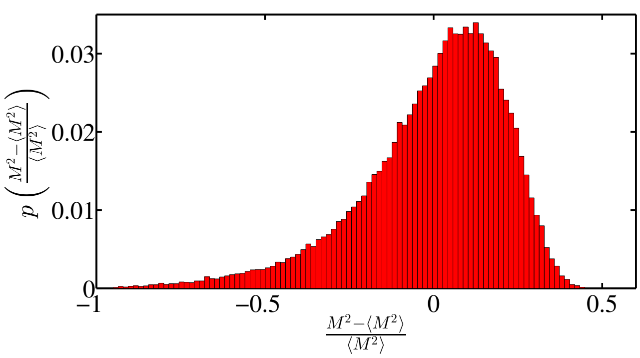

Figure 4: Probability distribution of the M^2 values determined using Monte Carlo simulation.

An input field distribution for GENESIS has been prepared using the measured profile shown in Figure 2 and the FEL performance has been calculated for the parameters listed in Table 1. Figure 5 shows the power contrast after the fourth undulator along the bunch. The simulated contrast is in a good agreement with the expected value for an M^2 of 2.2 in Figure 1 and also agrees with the experimentally measured energy contrast reported in [4]. In order to compare the results one has to stress that the ratio between the SASE photon pulse length and the seed pulse length is about 4. FEL pulse energy was $(1.3 \pm 0.5)\,\mu$J while the unseeded SASE pulse had an energy of about 300 nJ. The duration of the seeded FEL pulse is determined by the duration of the seed pulse of approx. 15 fs while the duration of the region in the bunch suited for SASE was 60 fs, measured using a transverse deflecting cavity. Shot-to-shot fluctuations have been averaged out.

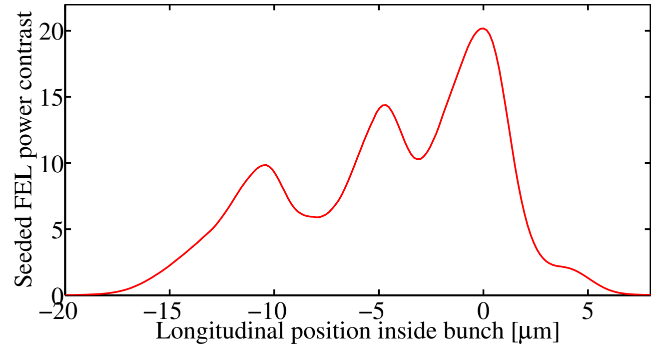

Figure 5: Power contrast along the internal bunch coordinate s.

CONCLUSION

It has been shown that the influence of the M^2 onto the power contrast is of high importance for the performance of a seeded FEL facility. The power contrast decreases strongly with M^2 , reaching 0 at an M^2 of about 5. Results of the studies of this dependence are in good agreement with the experimental data from "sFLASH", the HHG direct seeding experiment at FLASH. A method to obtain M^2 value has been discussed and used to evaluate properties of the HHG seed beam at FLASH. Seed pulse field distribution files have been generated. Therefore the modal content that has been reconstructed from intensity profiles. Those profiles were taken during the successful seeding. Simulation using these field distributions deliver results which are in good agreement with measured data.

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