INFLUENCE OF SEED LASER WAVEFRONT IMPERFECTIONS ON HGHG SEEDING PERFORMANCE

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Abstract

To enhance the spectral and temporal properties of a free-electron laser, the FEL process can be seeded by an external light field. The quality of this light field strongly influences the final characteristics of the seeded FEL pulse. To push the limits of a seeding scheme and reach the smallest possible wavelengths it is therefore crucial to have a thorough understanding of relations between laser parameters and seeding performance. In this contribution, we numerically study the influence of laser wavefront imperfections on high-gain harmonic generation seeding at the seeding experiment at FLASH.

INTRODUCTION

To overcome statistical fluctuations of the radiation generated by a free-electron laser (FEL) that starts up from noise, the FEL process can be seeded by an external coherent source. In case of seeding schemes like high-gain harmonic generation (HGHG), a laser is used to imprint a sinusoidal energy modulation on the electron bunch. The quality of this modulation and the resulting bunching is strongly determined by the imperfections of the seed laser.

Since it is not practical to place a wavefront sensor at the region of interaction within the modulator undulator in order to measure laser wavefronts directly, often only the transverse intensity profile on screens can be used to diagnose the light field. From these measurements one can measure the transverse laser spot size as well as calculate the beam quality factor M^2.

Typically, simulations of seeding schemes are conducted with a perfect wavefront of the seed light field. Such a laser beam has a beam quality factor of $M^2 = 1$. As the beam quality factor degrades, additional modes arise in the transverse profile and the intensity distribution as well as the phase of the laser degrades in quality. Figure 1 shows exemplary the intensity profile of a laser beam with $M^2 = 1.0$, $M^2 = 2.0$ and $M^2 = 3.0$.

Using numerical methods we have investigated the influence of wavefront imperfections with a beam quality factor of up to $M^2 = 5.8$.

NUMERICAL METHODS

All FEL simulations presented in this contribution have been conducted with GENESIS 1.3 [1]. The simulations have been conducted for the experimental seeding setup at FLASH1 [2]. The relevant parameters are given in Table 1.

The transfer matrix option of GENESIS 1.3 has been used in order to both match the beam into the radiator and introduce the right amount of dispersive strength to bunch the electron beam. Thus, this simulation does not include any collective effects.

Table 1: Simulation Parameters for FEL Simulations at the Seeding Experiment at FLASH

Lattice modulator		
Undulator period	λ_u	20 cm
Periods per undulator	N_u	6
Undulator parameter	K_{rms}	1.9
Lattice radiator		
Number of undulators		4
Undulator period	λ_u	31.4 mm
Periods per undulator	N_u	60 (4th one: 120)
Undulator parameter	K_{rms}	1.8
Laser pulse		
Wavelength	λ_L	267 nm
Peak power	P_L	300 MW
FWHM duration	$\Delta\tau$	50 fs
Electron beam		
Peak current	I_{max}	1500 A
Energy	E	675 MeV
Energy spread	σ_E	200 keV
Normalized emittance	$\epsilon_{n\,x}, \epsilon_{n\,y}$	1.5 mm mrad

To properly model the seed laser imperfections, a field file that gives the complex electric field on each point of a three-dimensional grid has been used. This field was generated with the numeric algorithm described in [3]. It is based on the description of partially coherent beams using Hermite-Gaussian modes and allows the Monte Carlo driven generation of a modal composition for a given value of M^2.

In order to keep the axial symmetry of the seed field, only TEM_{mn} modes with even m, n have been considered. Since there are many possible combinations generating the same beam quality factors, the one with the minimum number of modes has been chosen. The total beam size has been kept constant along all profiles of a simulation run leading to the TEM_{00} mode getting smaller and less intense with higher M^2 as can be seen in Figure 2.

SIMULATION RESULTS

For a sufficient modulation to be built up even for the higher values of M^2, we chose a seed laser peak power of 300 MW, a full-width half maximum seed duration of $\Delta\tau = 50$ fs and a FWHM spot size of the laser beam of 800 µm.

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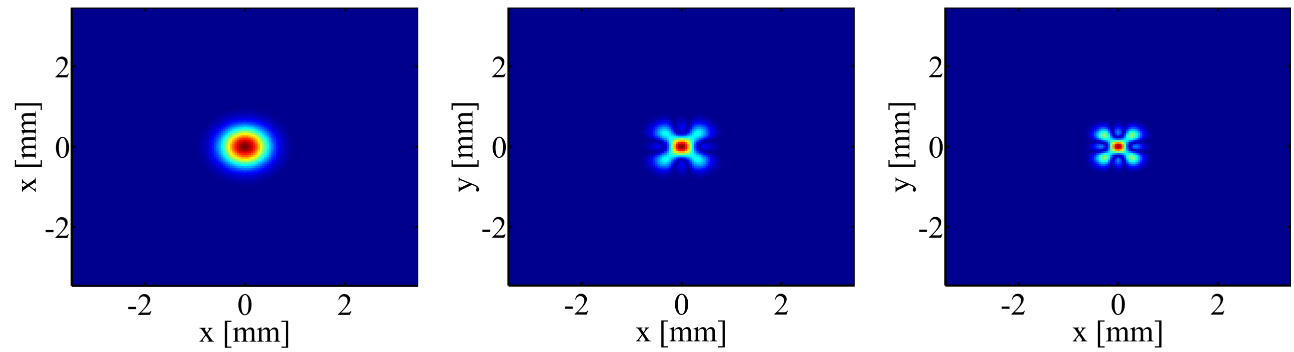

Figure 1: Transverse intensity profile of a laser beam with M^2 = 1.0 (left), M^2 = 2.0 (center) and M^2 = 3.0 (right). The color code shows the relative intensity on a linear scale, where dark red is the are with most intensity and blue is no intensity.

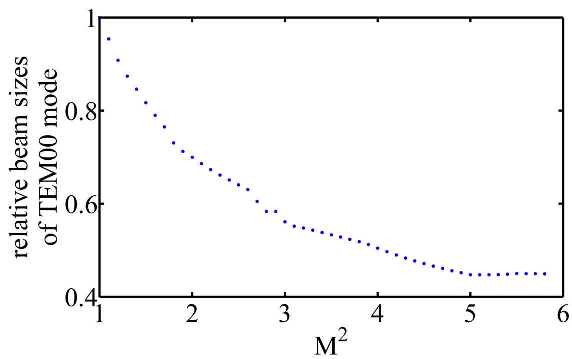

Figure 2: Relative transverse size of the TEM_{00} mode as a function of its beam quality factor M^2.

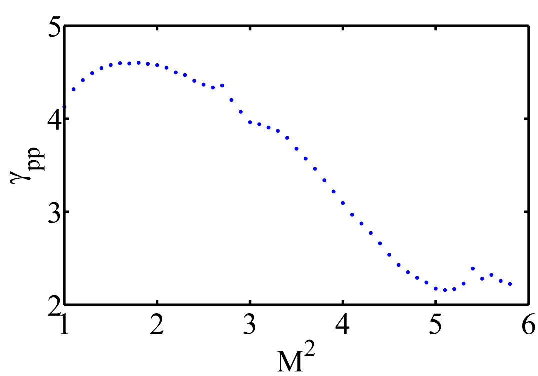

Figure 3: The modulation amplitude $\gamma_{\rm pp}$ induced by the seed laser as a function of its beam quality factor M^2.

Figure 3 shows the total modulation amplitude as a function of the M^2 of the seed light field. As seen before, the transverse size TEM_{00} carrying most of the beams intensity decreases with higher M^2. As new modes arise in the transverse profile also the power in the fundamental mode decreases.

The amplitude of the energy modulation decreases with higher M^2, since the TEM_{00} mode's intensity deacreses. Within the first few datapoints between M^2 = 1.0 and M^2 = 1.7 the modulation amplitude, however, rises. In this regime the transverse size of the TEM_{00} decreases faster than the square root of its power and thus the intensity rises.

For each particle distribution, the optimum R_{56} for bunching on the 7th harmonic of the laser wavelength has been calculated, and the transfermatrix of the corresponding chicane has been applied.

The resulting FEL power after the sFLASH undulator is shown in Figure 4. It decreases rapidly between M^2 = 4.0 and M^2 = 5.0 indicating a higher saturation length for the following runs.

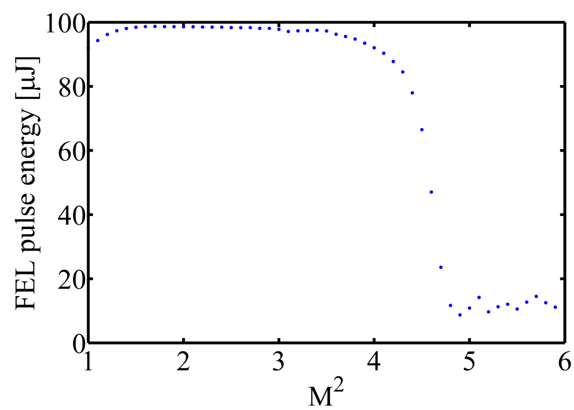

Figure 4: FEL pulse energy after the 4th radiator as a function of its beam quality factor M^2. The saturation energy increases rapidly between M^2 = 4.0 and M^2 = 5.0 and with this the power after the sFLASH undulators decreases.

Figure 5 shows a transverse map of the bunching phase of the bunched beam for M^2 = 5.0. The particle distribution has been binned transversely and the positions of the peaks with respect to the slice definition of GENESIS 1.3 have been analysed. For the outer layers, this analysis suffers from a small number of particles, further analysis will therefore focus on the central part of the bunch.

To further characterize the roughness of the wavefront, we have investigated the rms of all phases within a radius of $2\sigma_e$ in the electron bunch, where $\sigma_{\rm e}$ is its transverse rms width. Figure 6 shows these results as a function of M^2 of the input light field. It can be seen that the roughness increases at the same M^2 as the resulting FEL power decreases.

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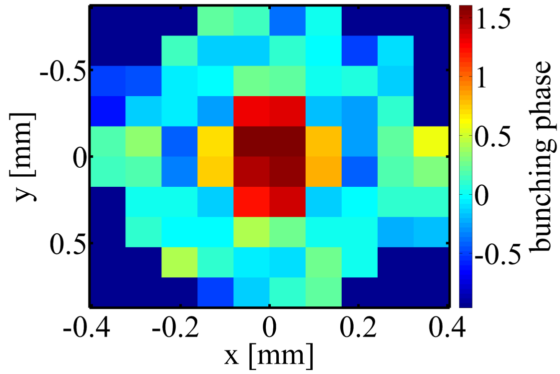

Figure 5: Transversely binned phase of the bunching in the electron bunch. The bunching is given in rad with respect to the center of one slice in GENESIS 1.3 for $M^2 = 5.0$.

The increasing roughness leads to a smaller bunching factor of the projected current distribution as already derived in [4].

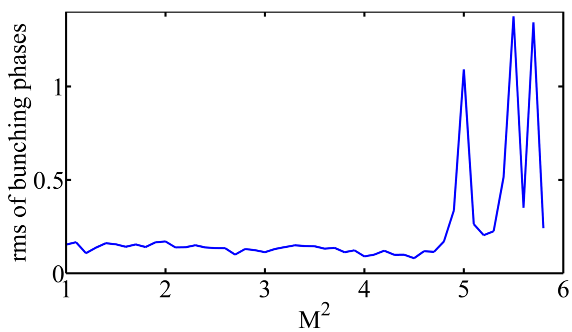

Figure 6: Roughness of bunching phases as a function of its beam quality factor M^2.

CONCLUSION AND OUTLOOK

The influence of the beam quality factor M^2 of a seed laser in an HGHG seeding setup has been studied considering the seeding hardware installed at FLASH1. With a seeding input power of 300 MW, the FEL signal at the end of the sFLASH undulator significantly decreases between $M^2 = 4.0$ and $M^2 = 5.0$. This is caused by the transverse inhomogeneous phase that results in a degraded bunchhing factor of the current profile and with this in an increased saturation length.

Future studies will analyse the characteristics of the resulting FEL pulse as well as the influence of different modal compositions for the same M^2. That will also determine the uncertainty of the study presented in this paper.

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