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HGHG schemes for short wavelengths

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ABSTRACT

In this paper, we discuss a method to design a single-stage high Gain Harmonic Generation (HGHG) scheme with the aid of GENESIS 1.3 numerical code. To properly design an HGHG scheme, shot-noise effects in both undulators as well as the effect of the energy spread induced by the FEL process in the modulator have to be taken into account. We design the device evaluating these undesired effects separately in each stage and simulating the joint effects on the final configuration. The method will be illustrated following the example of an HGHG scheme for the SPARX project.

1. High-gain harmonic generation in free electron lasers

High Gain Harmonic Generation (HGHG) [1,2] in FELs is one of the most promising alternatives to SASE FELs in the soft X-ray region. The advantages of HGHG over SASE are enhanced temporal coherence and the shorter saturation length.

A single-stage HGHG scheme is composed of two undulators separated by a dispersive section. The first undulator (called modulator) is tuned to the wavelength of a coherent external seed source. The FEL process in the modulator introduces an energy modulation in the electron beam on the scale of the resonant wavelength.

The dispersive section shifts the relative position of the electrons proportionally to their energy deviation, transforming the energy modulation into a density modulation. We have [2]

$$b_n = J_n\left(n\,\Delta p\,\frac{d\theta}{dp}\right)\exp\left(-\frac{1}{2}\left(n\sigma_p\,\frac{d\theta}{dp}\right)^2\right) \tag{1.1}$$

Δp is the relative energy modulation, σ_p is the uncorrelated energy spread and $(d\theta/dp) = (2\pi/\lambda)R_{56}$, where R_{56} is the 5–6 element of the transport matrix of the dispersive section. b_n has an optimum for $(d\theta/dp) = 1/\Delta p$. Assuming that we work close to this optimum condition we obtain:

$$b_n = \max(J_n)\exp\left(-\frac{1}{2}\left(n\frac{\sigma_p}{\Delta p}\right)^2\right). \tag{1.2}$$

The second undulator (called radiator) is tuned to a harmonic of the modulator resonant wavelength. The bunching factor on this harmonic triggers the FEL process in the radiator.

Single-stage HGHG operation is very challenging in the spectral region of soft X-rays, due to the high value of the equivalent shot-noise power at short wavelengths. A detailed numerical study of the shot-noise effects on the output radiation is essential to evaluate the feasibility of an HGHG-FEL at short wavelengths.

2. Design of a single-stage HGHG scheme with GENESIS 1.3

The preliminary design of an HGHG scheme consists of choosing the input seed power and the initial bunching factor at the radiator entrance.

The input seed power has to be high enough in order to overcome the effects of shot noise. The initial bunching factor at the radiator entrance has to be high enough to address the shot-noise effects but low enough to avoid loss of efficiency in the radiator due to the energy spread induced by the FEL process in the modulator.

We will take into account the shot-noise and energy spread effects separately and evaluate the joint effects on the final configuration.

We illustrate this method on the example of a fifth harmonic multiplication scheme for the SPARX FEL.

Table 1 shows the electron beam, radiation and undulator parameters.

2.1. Shot-noise effects in the modulator

The FEL process in the modulator is triggered by both the external seed radiation and the shot noise in the electron beam.

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Table 1
Electron beam, radiation and undulator parameters for the SPARX HGHG scheme

Electron beam	
Energy	2.3 GeV
Peak current	2.4 kA
Emittance	1 mm mrad
Uncorrelated energy spread	10^{-4}
Average RMS radius	42 μm
Radiation	
λ_{mod}	13 nm
λ_{rad}	2.6 nm
Modulator	
$\lambda_{w,mod}$	5.4 cm
$a_{w,mod}$	3.0659
Radiator	
$\lambda_{w,rad}$	2.7 cm
$A_{w,rad}$	1.7766

For the seeding to be efficient, we require the seed power to be much higher than the equivalent shot-noise power [3]:

$$P_s = \frac{3^{3/4} 4\pi\rho_{mod}^2 W_b}{N_\lambda \sqrt{\pi} \bar{z}_{mod}}. \tag{2.1}$$

ρ is the usual FEL parameter defined in Ref. [4], $\bar{z}_{mod}$ is the modulator length normalized to the gain length L_g–$\lambda_w/4\pi\rho$, W_b is the electron beam power and N_λ is the number of electrons in a wavelength.

From Eq. (2.1) follows that the equivalent shot-noise power depends on the length of the modulator. However, the length of the modulator is not known a priori as it depends on the seed power for a given final energy modulation. We will thus give a rough a priori estimate for the modulator length.

For the SPARX case, the one-dimensional estimate of the equivalent shot-noise power is

$$P_s \approx \frac{1\,\text{kW}}{\sqrt{\bar{z}_{mod}}}. \tag{2.2}$$

We expect the needed seed power to be at least two orders of magnitude above the shot-noise level. With a seed power of 100 kW and a 11.4-m long undulator, we have an energy modulation amplitude of about 5ρ. Due to the weak dependence of the equivalent shot-noise power on the longitudinal position, the results obtained on this undulator will stand also for the final configuration.

We evaluate the effect of the shot noise by carrying out time-dependent 3d simulations with GENESIS 1.3 [5] and studying the temporal coherence properties of the first harmonic radiation at the exit of the modulator [6]. We simulate a stepped profile for both the seed radiation beam and the electron beam.

For the seed pulse we assume a transverse Gaussian mode TEM00. The Rayleigh length is $Zr = 1.5$ m and the waist position is 1 m after the undulator entrance.

2.1.1. First-order temporal coherence

The first-order coherence function is defined as [7]

$$c_1(\tau) = \frac{\overline{\tilde{E}(t) \cdot \tilde{E}^*(t+\tau)}}{\overline{|\tilde{E}(t)|^2}} \tag{2.3}$$

$\tilde{E}(\tau)$ being the slowly varying field amplitude defined by the relationship:

$$E(t) = \Re(\widetilde{E(t)} \exp(i\omega t)),$$

and the overlined expressions are averaged over t.

We can evaluate the coherence length as [7]

$$L_c = \int |c_1(t)|^2\, dt. \tag{2.4}$$

In Fig. 1 the coherence length of the first harmonic radiation is shown as a function of the seed power.

The coherence length grows monotonically with the input power until it reaches a value of $2/3L_b$, which is the coherence length of a fully coherent radiation beam of length L_b with a step profile.

From Fig. 1 follows that first-order temporal coherence is achieved with an input power of tens of kiloWatts.

2.1.2. Second-order temporal coherence

Fig. 2 shows the RMS amplitude of the intensity fluctuation of the first harmonic radiation at the modulator exit, as a function of the input power. $\sigma_1/\bar{I}$ is a monotonically decreasing function of the input power. We obtain an acceptable value for the fluctuations (less than 3%) for an input power of hundreds of kiloWatts.

2.2. Shot-noise effects in the radiator

The FEL process in the radiator is triggered by the initial bunching factor on the fifth harmonic and by the shot noise.

In order for the coherent harmonic bunching to be efficient we require:

$$|b_{0,5,c}|^2 \gg \frac{3^{3/4} 4\pi\rho_{rad}}{N_{\frac{\pi}{\lambda}} \sqrt{\bar{z}_{rad}}}. \tag{2.5}$$

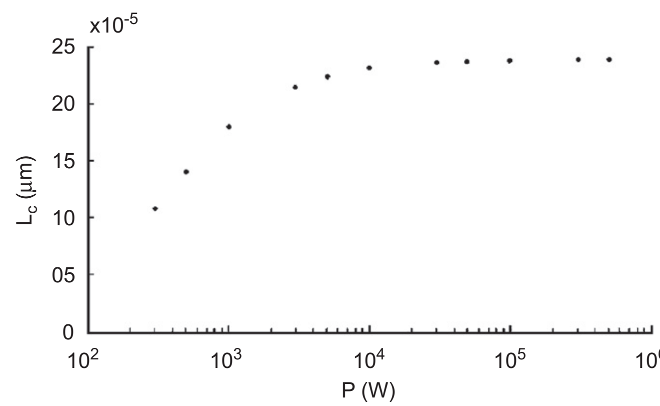

Fig. 1. Coherence length of the first harmonic radiation at the modulator exit as a function of the input power.

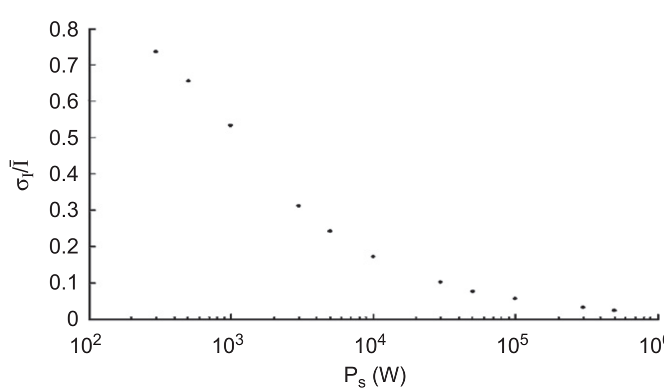

Fig. 2. RMS relative intensity fluctuations amplitude of the first harmonic radiation at the modulator exit as a function of the input seed power.