A COMPARISON BETWEEN HIGH-GAIN HARMONIC GENERATION AND SELF-SEEDING FOR THE PRODUCTION OF NARROW BANDWIDTH RADIATION IN A FREE-ELECTRON LASER

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Abstract

In this paper we investigate and compare the properties of two narrow bandwidth free-electron laser (FEL) schemes, one using self-seeding and the other high gain harmonic generation (HGHG). The two systems have been thoroughly studied analytically and numerically in the past. The aim of this work is to compare their performances when the FEL is driven by an electron beam with non-ideal properties, thus including effects such as shot-to-shot energy fluctuations and nonlinear energy chirp. In both cases non-linearities produce a bandwidth larger than the Fourier transform limited value. However the results of our analysis indicate that the self-seeding scheme is less affected by non-ideal electron phase space distribution than the HGHG seeding scheme and thus has a larger number of FEL photons per unit frequency.

INTRODUCTION

The unique characteristic of an FEL, with respect to other sources of electromagnetic radiation based on the emission from relativistic electrons, is the large number of photons in the coherent volume. However, while a SASE source is practically diffraction limited [1], its bandwidth is determined by the FEL cooperation length [7]. This means that the bandwidth is larger than the Fourier transform limit, except for the case when the electron bunch is short with respect to the cooperation length, and only a single spike is present in the radiation pulse. When the electron bunch is longer than the cooperation length, and many spikes are present in the output pulse, the number of photons in a coherent volume could be further increased by reducing the bandwidth to the transform limit or near to it. Several schemes have been proposed to achieve this goal and reduce the bandwidth with respect to that achievable with SASE. In this paper we will consider two such schemes: self-seeding [12] and high gain harmonic generation (HGHG) [19], [6] with seeding from high harmonic generated in gas (HHG) [13], [16].

The self-seeded FEL consists of two undulators separated by a monochromator and a magnetic chicane. The FEL process in the first undulator is started by shot noise and is interrupted well before saturation. While the SASE radiation is sent through a monochromator the electron beam passes through a magnetic chicane which destroys the microbunching introduced by the SASE and compensates the delay introduced by the monochromator. The monochromatic radiation and the demodulated electron beam are then sent through the second undulator for a seeded FEL process reaching saturation.

Table 1: Electron Beam Parameters

Electron Beam Parameters	
Energy	1.5 GeV
Peak Current	1.5 kA
Uncorrelated Energy Spread σ_p	10^{-4}
Normalized Emittance	1 mm× mrad
RMS Bunch Length σ_s	55 µm

The FEL in the HGHG case is composed of two undulators separated by a magnetic chicane. The first undulator, called modulator, is seeded by an external coherent source. The FEL interaction in the first undulator introduces an energy modulation in the electron beam. The dispersive section transforms the energy modulation in a density modulation on higher harmonics of the seed wavelength. The second undulator, called radiator, is tuned to one of these harmonics. The bunching factor generated by the dispersive section triggers the FEL process in the second undulator.

THE IDEAL ELECTRON BEAM AND LASER CASE

The comparison between HGHG and self-seeding is carried out using the electron beam parameters of the 1 nC, 1.5 GeV working point of the SPARX FEL [15], shown in Table 1. The ideal FEL characteristics are given in Table 2. As an idealized case we assume a beam with a flat energy distribution and a gaussian current distribution. We operate the FEL at a wavelength of 6 nm, for the HGHG case we assume a 30 nm seed with 5^{th} harmonic conversion. For the self-seeded scheme both undulators have a 2.8 cm period, while in the HGHG case the period is 4.2 cm for the modulator and 2.8 cm for the radiator. For a 55 µm rms bunch length the transform limited relative bandwidth at the chosen wavelength is 2×10^{-5} full width at half maximum (FWHM).

For the self-seeding we assume a monochromator with a bandwidth of 3×10^{-5} and 20% transmissivity. A choice of 410 periods (L_1 = 11.5 m) for the first undulator gives an average peak power after the monochromator of 60 kW,

Table 2: FEL Parameters

FEL Parameter	
Wavelength	6 nm
FEL parameter ρ	2.2×10^{-3}
Gain Bandwidth $\Delta\lambda_{gain}/\lambda$	2.2×10^{-3}
Transform Limited Relative Bandwidth $\Delta\lambda/\lambda_{FWHM}$	2×10^{-5}

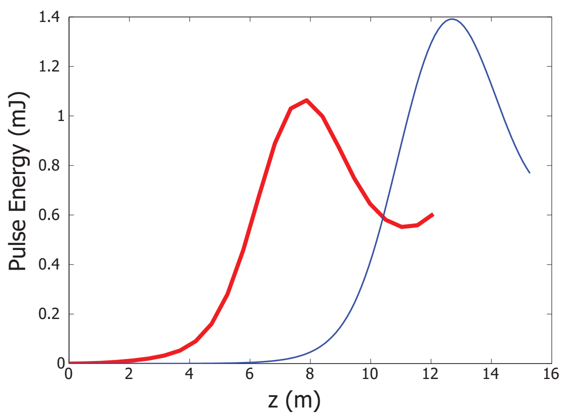

Figure 1: Radiation pulse energy as a function of the position along the second undulator for the self-seeding (blue line) and for the HGHG (red thick line). The results for the self-seeding are averaged over 20 independent simulations.

well above the shot noise level (roughly 300W). Saturation in the second undulator is reached in $L_{sat} = 13$ m. The results of 1-D time dependent simulations with PERSEO [14] are shown in Figures 1 and 2. The saturation energy is ≈ 1.4 mJ, in a full width at half maximum (FWHM) bandwidth of $\Delta\lambda/\lambda_{FWHM} = 4.2 \times 10^{-5}$.

In the HGHG case, the seed source has a central wavelength of 30 nm. To tune the modulator to such wavelength, the undulator period is 4.2 cm and the undulator parameter is K=4.41. We assume a seed power of 100 kW, which provides an energy modulation amplitude of $4\sigma_p$ after 130 undulator periods(L_{mod}= 3.6 m). The optimum value for the dispersive section strength is $R_{56} = 10^{-5}$ m, which gives a fifth harmonic bunching factor of $b_5 = 0.1$. In the ideal case we assume a Fourier transform limited pulse with a length equal to the electron pulse for the HHG seed. Saturation in the radiator is reached in L_{sat}= 8 m, resulting in a total undulator lentgh of $L_{tot} = 11.6$ m . The saturation energy is ≈ 1 mJ over a relative FWHM bandwidth of $\Delta\lambda/\lambda_{FWHM} = 6.8 \times 10^{-5}$ (see Figures 1 and 2).

EFFECT OF NON-LINEAR ENERGY CHIRP

A non-linear energy chirp in the electron beam is responsible for spectral broadening in the radiation pulse. In both schemes spectral broadening is due to the imaginary part of the gain varying with energy along the bunch and resulting

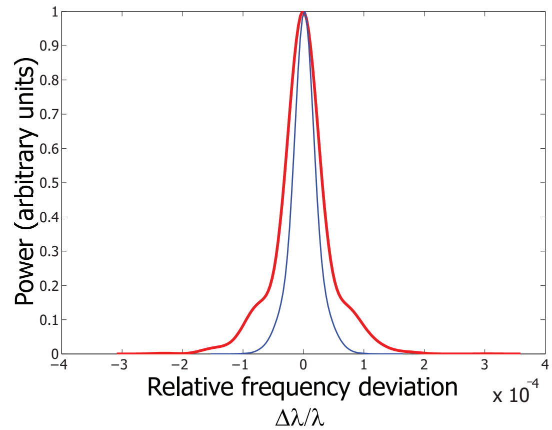

Figure 2: Spectrum at saturation for the self-seeding (blue line) and HGHG (red thick line) schemes. FWHM bandwidths are respectively 4.2×10^{-5} and 6.8×10^{-5}.

in a non-linear phase chirp in the radiation pulse. Following the one dimensional model of the FEL and neglecting the effect of slippage, we obtain the following expression for the phase of the electric field [8]:

$$\psi(s) = -2k_w z p(s) + \Re\{\Lambda(p(s))\}2k_w z\rho. \quad (1)$$

We allow the beam energy to have a dependence on s. Taking the derivative of Equation (1) with respect to s and linearizing $\Re\{\Lambda(p)\}$ we can express the local frequency offset as:

$$\frac{\delta\lambda(s)}{\lambda} = 2N_w\lambda\frac{dp}{ds} - \frac{1}{2\pi}\frac{\lambda}{3\rho}\frac{dp}{ds}N_w\lambda_w 2k_w\rho = \frac{4}{3}N_w\lambda\frac{dp}{ds}. \quad (2)$$

In a quadratically chirped beam $\frac{dp}{ds}$ varies with position, resulting in a frequency modulated radiation pulse with a broader bandwidth than the transform limited case.

HGHG suffers from an additional broadening effect due to the quadratically chirped beam passing through a dispersive section which results in a local frequency offset of [5], [18]:

$$\frac{\delta\lambda(s)}{\lambda} = R_{56}\frac{dp}{ds}. \quad (3)$$

In the HGHG scheme contributiona from both the undulators have to be summed and the total local frequency offset :

$$\frac{\delta\lambda(s)}{\lambda} = [\frac{4}{3}\lambda(nN_{mod} + N_{rad}) + R_{56}]\frac{dp}{ds} \quad (4)$$

where N_{mod} and N_{rad} are respectively the number of periods of the modulator and the radiator.

Inserting the parameters of section in Equations (2) and (4), we obtain:

$$\frac{\delta\lambda(s)}{\lambda}_{HGHG} \approx 5 \times \frac{\delta\lambda(s)}{\lambda}_{self-seeding}. \quad (5)$$

Figure 3 shows the FWHM bandwidth as a function of the amplitude of the quadratic energy chirp for the schemes

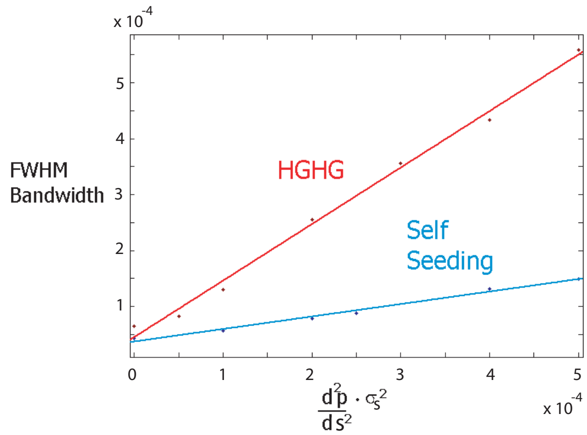

Figure 3: FWHM bandwidth at saturation as a function of the quadratic chirp amplitude. The results for self-seeding are averaged over 20 independent runs.

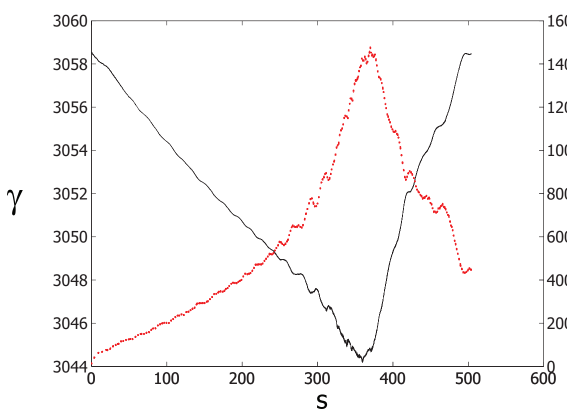

Figure 4: Slice normalized energy (black solid line) and current (red dashed line) as a function of position along the beam for the SPARX 1.5 GeV, 1 nC beam, obtained from a start-to-end simulation.

described in section (the spectra are calculated with the PERSEO FEL code). In the example considered the spectral broadening is almost 5 times bigger for the HGHG scheme, a result that is consistent with the analytical estimate. The consequence of this sensitivity is that particular care has to be given to the optimization of the electron beam longitudinal phase space for seeded operation [11].

START TO END SIMULATIONS

The performances of the two schemes have been investigated using a start to end simulation for the SPARX FEL to evaluate the effect of non-ideal beam characteristics. The results at the 1.5 GeV, 1 nC working point [15] are shown in Figure 4.

In the self seeded scheme the first undulator is made of 7 sections of 75 periods. Assuming a 20% efficiency and 3×10^{-5} bandwidth for the monochromator, the average radiation power at the second undulator entrance is 60 kW. The magnetic chicane has an R_{56} of 100 µm. The simulations have been carried out with GENESIS 1.3 [17] and ELEGANT [9]. The results of the start to end simulations are reported in Figures 5, 6. The FEL saturates in the second undulator in $L_{sat} = 20.5$ m. Including the magnetic chicane, the total length of the self-seeded system is $L_{tot} = 51.2$ m. The saturation energy is ≈ 0.9 mJ in a FWHM bandwidth $\frac{\Delta\lambda}{\lambda}_{FWHM} = 5 \times 10^{-5}$.

Table 3: Seed radiation parameters for the HGHG scheme.

Seed Radiation Parameters	
Bandwidth $\frac{\Delta\lambda}{\lambda}_{seed}$	5×10^{-4}
Duration	100 fs
Peak Power	10 kW

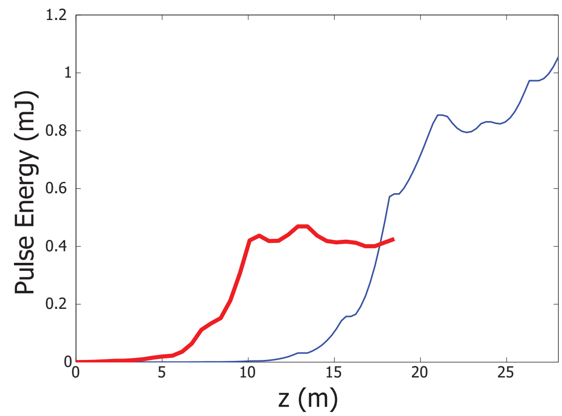

Figure 5: Start to end pulse energy along the second undulator for the self-seeding (blue line) and for the HGHG (red thick line). The results for the self-seeding are averaged over 50 independent simulations.

For the HGHG case, the parameters of the seed source are reported on Table 3. These parameters represent the state of the art for HHG in gas sources at 30 nm [10]. The radiator has an undulator period of 2.8 cm and is composed of sections of 75 periods. The modulator is made of 3 sections of 55 periods each, with period of 4.2 cm ($L_{mod} = 7$ m). With this setup we obtain an 8% harmonic bunching factor at the radiator entrance. The results of the start to end simulations with GENESIS 1.3 are reported in Figures 5 and 6. The FEL saturates in the radiator in $L_{sat} = 10.5$ m, giving a total length of $L_{tot} = 17.5$ m. The saturation energy is ≈ 400 µJ in a FWHM bandwidth of $\frac{\Delta\lambda}{\lambda}_{FWHM} = 5.8 \times 10^{-4}$. Note that the bandwidth is almost six times bigger than the Fourier transform limit (with a seed bandwidth of 5×10^{-4}, the transform limited output bandwidth for the fifth harmonic would be 10^{-4}).

CONCLUSIONS

We have addressed specific problems related to narrowing the FEL bandwidth with self-seeding and with HGHG.

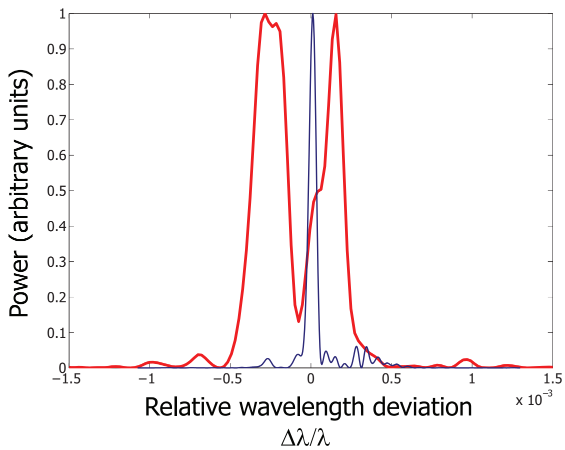

Figure 6: Start to end, spectrum at saturation for the self-seeded scheme (blue line) and for the HGHG scheme (red thick line). FWHM bandwidths are respectively 5×10^{-5} and 5.8×10^{-4}. The results of the self-seeded scheme are averaged over 50 independent simulations.

In the ideal case the self-seeding and HGHG schemes have about the same performance whereas in the start-to-end case the results are significantly different. The simulations carried out in the start to end case using a realistic electron beam phase space optimized for SPARX SASE operation and state of the art seed parameters, show that the performances of the self-seeded scheme exceed those of HGHG by a factor 25 in terms of spectral power density, due to the spectral broadening associated to non linear longitudinal phase space and to the short duration of the seed pulse. The electron beam energy chirp may be reduced by operating with lower compression and by paying special attention to the optimization of the longitudinal phase space, however it must be noted that low current operation would result in a lower saturation power, reducing the advantages deriving from a more linear longitudinal phase space. The limitations on the seed pulse duration can be overcome by an increased pulse energy and a tighter monochromatization prior to injection. A progress in the HHG sources brightness in the wavelength range considered in this paper, would provide a significant improvement in the implemetation of such sources in seeding FELs.

Furthermore, this work emphasizes the importance of start to end simulations as a tool for reliably predicting the performances of narrow bandwidth FELs.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Doctor A. Zholents and Doctor E. Hemsing for useful discussions and suggestions. The authors are also grateful to Doctor C. Vaccarezza and the SPARX project team for sharing the results of the start to end simulations and Doctor L. Poletto for many useful discussions on short pulse monochromatization and monochromator efficiency. This work was supported by grants from Department of Energy Basic Energy Science Contract No. DOE BES 4-444025-RS-21830.

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