ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP077

STUDY OF A SEEDED OSCILLATOR-AMPLIFIER

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Abstract

In recent years, there is interest of the Free-Electron Laser (FEL) community in external-seeding techniques such as the Echo-Enabled Harmonic Generation (EEHG) and the High-Gain Harmonic Generation (HGHG). With these techniques, pulses of an improved temporal coherence are generated, but at the same time, they are limited by the repetition rates that seed lasers can currently offer with the required pulse energies. A big challenge is to combine the advantages of seeding schemes with high repetition rates. For this purpose, we study a combination of an oscillator-amplifier. The modulator in the oscillator is used at a long wavelength to modulate the electron beam and an amplifier is operated to extract the FEL radiation of the desired harmonic. This way we can use a seed laser of 10 Hz in a burst mode and a resonator to feedback the radiation at repetition rates of superconducting accelerators instead of using an external seed at these high-repetition rates. In this contribution, we present simulation results of a seeded oscillator-amplifier FEL in an HGHG scheme.

INTRODUCTION

For over ten years, SASE FELs have been delivering radiation to users in XUV and X-ray wavelength range [1]. Wavelengths from 100 nm down to below 0.1 nm have been achieved with 100 to several thousand pulses per second. In more recent years, several user facilities have improved the radiation properties by using different seeding schemes, mostly external seeding [2–4] and self-seeding at shorter wavelengths [5]. The next development that is planned is to go towards continuous wave (CW)-operation with superconducting accelerator technology, thus increasing the number of pulses per second to a million [6, 7]. A big challenge is to improve the radiation properties at high repetition rates and at short wavelengths simultaneously. Present schemes that use an external laser are investigating the possibility to work with superconducting machines such as FLASH and XFEL which could reach repetition rates of 1 MHz and 4.5 MHz respectively.

A system of an oscillator-amplifier has been studied in the past [8–11] and more recently as a high-gain oscillator with time-dependent three-dimensional simulations [12, 13]. The system was successfully studied up to the third harmonic of the initial frequency and, in all cases, the process was starting by amplifying the initial shot noise. It should be noted that since the initial studies the mirror and laser technology have been improved and at the same time, the simulation codes have been further developed allowing a more systematic and detailed study.

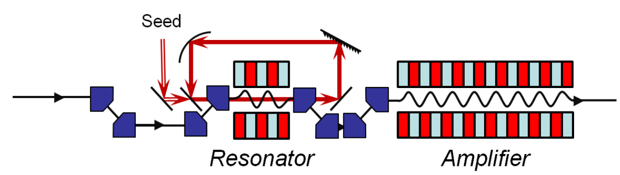

Figure 1: A possible design for the implementation of an HGHG seeded Oscillator-Amplifier.

THE LAYOUT

High-Gain Harmonic Generation [14] is a seeding scheme that is normally realized in a single-stage. In this process, the electron beam energy is modulated with a seed laser in the modulator, which is an undulator tuned to be resonant with the frequency of the seed laser. The energy modulation is converted into a density modulation in a dispersive section of a longitudinal dispersion R_{56}. After achieving the required density modulation for the desired harmonic of the seed laser, the electrons enter the radiator which is tuned to be resonant with the chosen harmonic of the seed laser. This scheme is aiming at fully coherent FEL radiation.

The layout under study is shown in Fig. 1. The process of a seeded oscillator-based HGHG, which will be referred to as a "multi-pass HGHG" in this contribution, is following the same principles of a "single-pass HGHG". The electron and the laser beam interact along the modulator to achieve energy modulation. Even though the energy modulation required can be achieved in a short distance, such as 2 gain lengths [14], in this case we use a longer undulator to achieve higher gain and compensate for the cavity losses. The radiation generated in one pass along the modulator is following the optical elements of the cavity and is redirected back to the beginning of the modulator for the next pass. The length of the cavity must be such that the roundtrip time of the radiation after travelling one time within the cavity is synchronised with the bunch separation. The cavity can in principle consist of simple transportation mirrors. Additionally, a monochromator (grating) and a focusing mirror can be added. Diagnostics could also be installed along this photon beamline for further control. The electron beam, after leaving the modulator, is guided to the next section through the bunching chicane. Finally, it generates radiation at a harmonic of the modulator wavelength in the amplifier.

In our studied cases, the FEL process starts with a seed laser of 300 nm or 50 nm. For the ultraviolet (UV) seed laser, a regular seed laser could be used to initiate the process,

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while for the 50 nm an HHG source can be chosen [15]. The target harmonic for the simulations presented is the 10th, therefore, the output wavelengths are 30 nm and 5 nm for the 300 nm and 50 nm seed laser, respectively.

SIMULATIONS

All simulations are performed with Genesis 1.3 version 4 in a time-dependent mode [16]. The simulation parameters are presented in Table 1. The field manipulation is done with Ocelot [17]. For the simulations, a fresh electron bunch is used along with an input seed laser for the first pass. At the end of the modulator, the field distribution is saved and the electron bunch continues in Genesis and travels in the chicane and later in the amplifier. The manipulated field file is loaded into Genesis for the next pass in the modulator in which it overlaps with a fresh bunch. Ocelot can be used, among other functions, to implement the slippage effect, monochromatize, focus, propagate and diagnose the field in each pass. In the simulations presented here, the field is only shifted longitudinally to simulate the slippage effect and its amplitude is reduced to include the intracavity losses.

Table 1: Simulation Parameters

Electron beam		
Energy	750 MeV	1350 MeV
Unc. energy spread	120 keV	120 keV
Peak current	1 kA (Flat-top)	1 kA (Flat-top)
Seed laser		
Wavelength	300 nm	50 nm
Input power	10 MW	80 MW
Chicane		
R_{56}	-32 µm	-12 µm

Results at 300 nm *Modulator and* 30 nm *Amplifier*

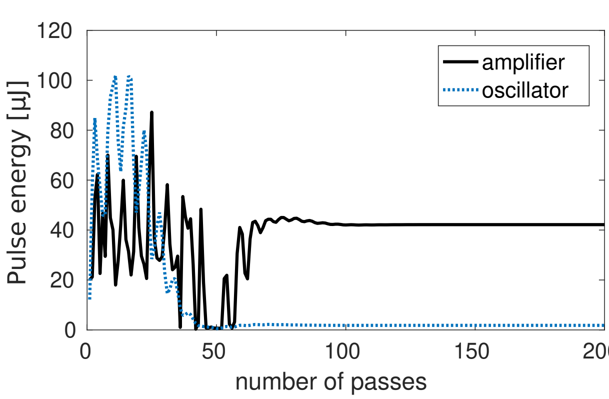

Figure 2: Multi-pass HGHG with a 300 nm-wavelength seed laser with a target final wavelength of 30 nm. Comparison of pulse energy evolution at the end of the modulator and at the amplifier as a number of passes.

The simulations start with a 300 nm-wavelength seed laser of 10 MW peak power which is used only for the first pass. The electron beam energy is 750 MeV and we have assumed resonator losses of 43% per roundtrip. In Fig. 2 we see the pulse energy at the end of the modulator and the end of a 10.3 m long amplifier for 200 passes. One can see that for the first 70 passes the energy follows some oscillations before it finally stabilizes and then, the optimized R_{56} enables a clean output spectrum as can been seen in Fig. 3a. The start-up process is currently under study. The calculated FWHM spectra bandwidth is $3.8{\cdot}10^{-3}$ for a final 10 fs FWHM photon pulse.

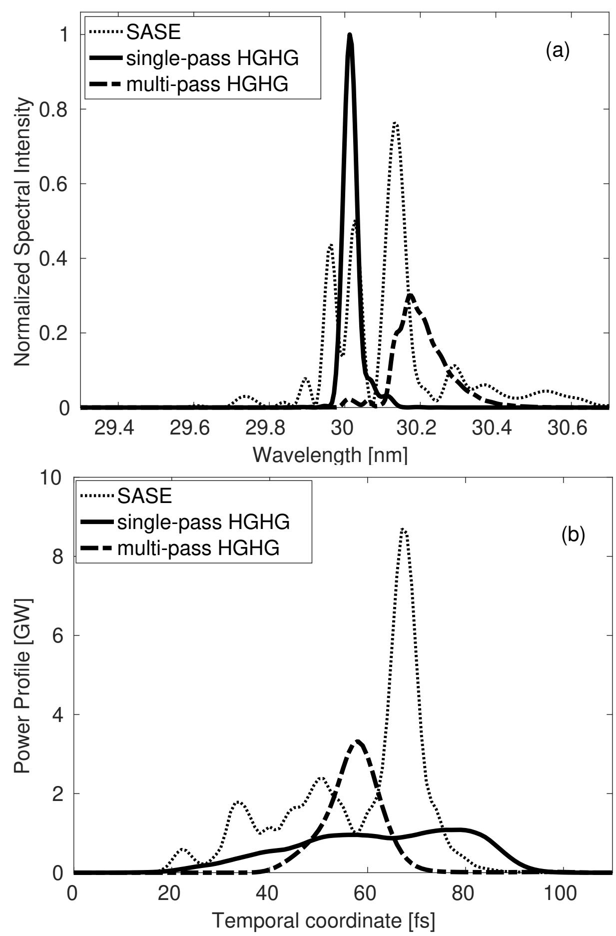

Figure 3: (a) Spectra comparison for a target wavelength of 30 nm with the same initial parameters and lattice. In (b) we compare the output power profile for the same cases.

Based on the calculated energy modulation and bunching induced at the end of the chicane after stabilization, we have performed a single-pass HGHG simulation. The initial parameters are the same and one can see the calculated spectrum of the simulated single-pass HGHG in Fig. 3a. The calculated FWHM bandwidth in this case is $1.2 \cdot 10^{-3}$ for a final 47 fs FWHM pulse. It should be noted that the radiation pulse in the oscillator is getting shorter due to the slippage effect until it stabilizes. This shortening of the pulse duration is leading to the bandwidth broadening in the

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frequency domain. Finally, in the same figure, we present the optimized SASE spectrum simulated with a 2.5 kA peak current electron bunch and at optimal position along the amplifier. In Fig. 3b we show the final power profiles in the amplifier. For the multi-pass HGHG simulation, we observe that the peak power exceeds 3 GW, but the pulse duration is considerably shorter even though the process starts with the same seed laser duration as the single-pass HGHG.

Results at 50 nm *Modulator and* 5 nm *Amplifier*

For this working point, a 50 nm-wavelength seed laser of 80 MW peak power is used for the first pass and an electron beam energy of 1350 MeV. The system is studied for 200 passes. In this case, the gain length is longer and therefore the amplification per pass is lower, the tolerances are tighter for the bunching and a dispersive section of a lower longitudinal dispersion is required. In addition, the losses in the cavity at this wavelength are higher. In this preliminary study, we assume 50% roundtrip losses.

In Fig. 4 we see the pulse energy at the end of the modulator and the end of a 20 m long amplifier. The energy at the oscillator, and therefore at the amplifier, is stabilized after roughly 80 passes. Finally, in Fig. 5a we see the output spectrum at the 159th pass. The calculated FWHM bandwidth is $1.1 \cdot 10^{-3}$ for an 8 fs final radiation pulse duration. Even though the peak pulse power exceeds 2 GW as it is shown in Fig. 5b, the energy remains on average at 19.9 µJ because of the pulse shortening in the cavity and hence, in the amplifier.

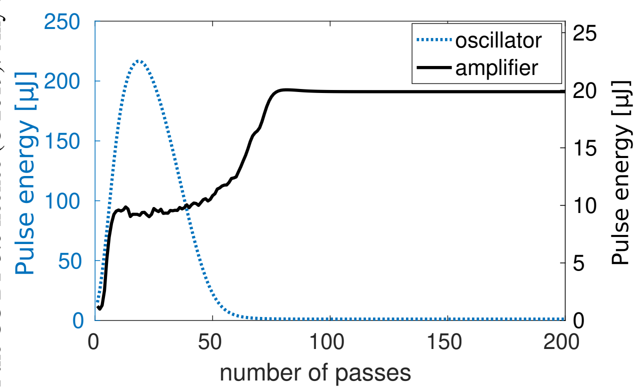

Figure 4: Multi-pass HGHG with a 50 nm-wavelength seed laser with target final wavelength of 5 nm. Comparison of pulse energy evolution at the end of the modulator and at the amplifier as a number of passes.

In addition, we show in Fig. 5a the final spectrum for a single-pass HGHG optimized for the modulation amplitude achieved in the multi-pass HGHG after stabilization and the same initial electron beam parameters. The calculated FWHM bandwidth in this case is $1.48 \cdot 10^{-4}$ for a final 75 fs pulse. Similar to the 30 nm case, we see that the short pulses in the cavity are leading to a broadening of the bandwidth. Finally, the optimized SASE spectrum is shown in the same figure for an electron bunch of 2.5 kA peak current at saturation, for completeness.

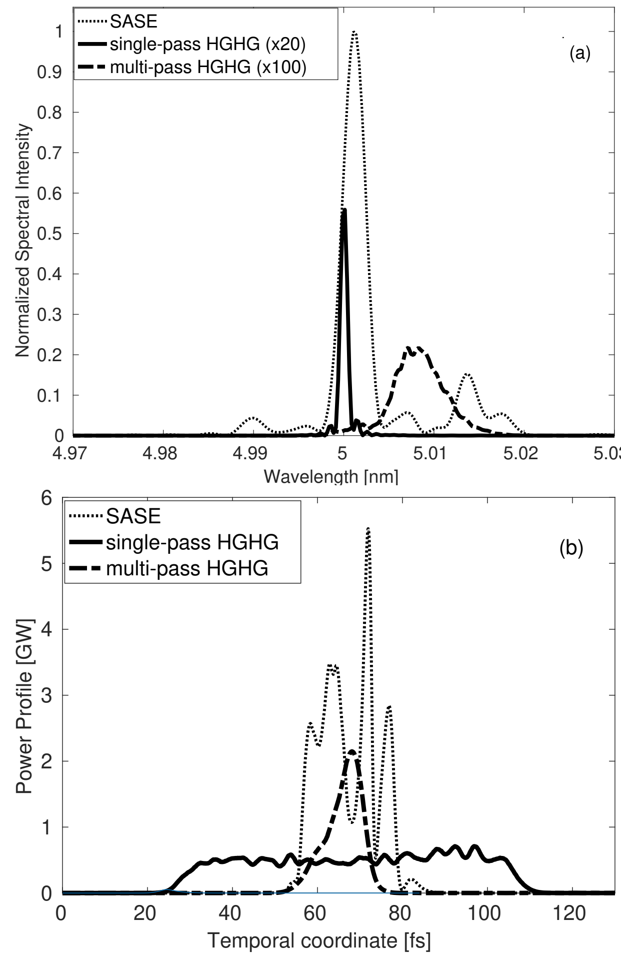

Figure 5: (a) Spectra comparison for a target wavelength of 5 nm for a SASE, a single-pass, and a multi-pass HGHG. Notice that the spectra of HGHG have been rescaled. In (b) we compare the output power profile for the same cases.

OUTLOOK

In this contribution, we showed simulation results for a multi-pass HGHG with target wavelengths of 30 nm and 5 nm. Further studies on the startup process and on the control of the field in the resonator are underway. These include the study of the focusing effect, the impact of monochromatization and the control of the duration of the radiation pulses in the resonator. This optimization aims at the improvement of the start-up process to reach a stationary state after a few passes and the improvement of the spectral properties. In addition, for the 5 nm case, a study of the same layout for higher losses is planned. Finally, the study of a multi-pass EEHG is foreseen. Further options and considerations on alternative layouts can be found in [18].

ACKNOWLEDGMENTS

I would like to thank Mykola Veremchuk for adding a Genesis 4 radiation field writing procedure to OCELOT.

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP077

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