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PATH TO HIGH REPETITION RATE SEEDING: COMBINING HIGH GAIN HARMONIC GENERATION WITH AN OPTICAL KLYSTRON

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Abstract

External seeding in combination with harmonic generation has become a hot topic in the field of high gain free-electron lasers (FELs) since it allows delivery of superior FEL radiation characterized by, for example, full coherence and unprecedented shot-to-shot stability. At low repetition rate machines operating at few 10 Hz, novel experiments have been realized already, however, at superconducting machines, current laser technology does not support exploiting the full repetition rate available. One way to overcome this problem is to reduce the requirements in seed laser power: here, an optical klystron based high gain harmonic generation (HGHG) setup is proposed to reduce the laser peak power requirements by orders of magnitude, enabling operation at drastically increased repetition rates. We report simulation results based on the seeded beamline concept of the FLASH2020+ project. Among other topics, the effect of a linear electron beam energy chirp on this setup will be discussed.

INTRODUCTION

In the fast-moving world of high-gain FELs [1], the FEL facilities worldwide aim at improving the properties of the radiation to accommodate innovative experiments that depend on special features, such as short pulse duration, high average flux and small bandwidth, to name a few. One popular milestone in high-gain FELs is the generation of fully coherent radiation at a high repetition rate. With more and more facilities being able to generate electron bunches at high repetition rates, such as the already-under-operation FLASH [2] and the European XFEL [3], and the upcoming LCLS II [4] and SHINE [5], it is possible to generate partially longitudinally coherent FEL pulses at MHz repetition rates with techniques like the self-amplified spontaneous emission (SASE) [6, 7]. On the other hand, external seeding techniques provide fully coherent FEL pulses but depend on the limited repetition rate of available seed laser sources. The necessary high peak laser power, of tens to hundreds of MW at the interaction point, practically limits the repetition rate to tens of Hz when the wavelength of seeds spans the ultraviolet (UV) range.

To overcome this hurdle, it has been proposed [8, 9] to combine the high gain harmonic generation (HGHG) [10, 11] with another well-established scheme: the optical klystron (OK) [12]. Adding the optical klystron to the standard HGHG scheme allows us to reduce the required laser peak power allowing to operate at a higher repetition rate. In the following, we compare with three-dimensional and time-dependent simulations the output FEL pulses of a standard HGHG scheme and an OK-HGHG scheme and we verify the lower seed laser power required by the latter. In addition to these results, we investigate the impact of a linear correlation between the energy and longitudinal position of the electrons (linear energy chirp), which commonly exists at several FEL facilities as it is a fundamental ingredient for achieving short electron bunches. We present the key considerations to reoptimize the two setups under these conditions and we investigate whether such a linear energy chirp is detrimental to the FEL pulse properties.

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THE LAYOUT

In standard HGHG, a modulator, a chicane and a radiator are required, as shown in Figure 1. The electron bunch interacts with the powerful seed laser along the modulator and, as a result, its energy is modulated. When traversing the chicane, higher-energy electrons take shorter paths and lower-energy electrons take longer paths, resulting in periodic longitudinal density modulations, quantified by the so-called bunching factor. If the energy modulation is sufficient, bunching at a harmonic of the seed laser wavelength can be obtained, resulting in fully coherent FEL pulses at that wavelength.

In OK HGHG, an additional modulator and chicane are required, as shown in Figure 2. The advantage here is that the seed laser power in the first modulator is much lower, as only a small energy modulation amplitude (in the order of the uncorrelated energy spread) is needed. With the assistance of chicane 1, microbunches are created with no need for harmonic content. In this way, the initially small energy modulation can be further self-amplified in modulator 2 and reach an amplitude that allows chicane 2 to induce bunching at harmonics of the seed laser wavelength.

SIMULATION RESULTS

To verify the efficiency of the OK HGHG scheme in comparison to the standard HGHG scheme, we simulated both of them with Genesis 1.3 [13] and optimized the simulations to generate the 15th harmonic of 300 nm seed laser wavelength (20 nm). For the beamline, electron beam, and laser parameters (see Table 1) we have based our study on the design parameters of FLASH2020+ [14], the upgrade project of FLASH. As a first step, we assumed an electron

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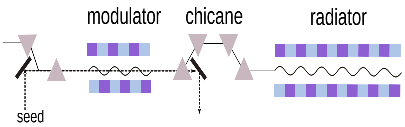


Figure 1: In the standard HGHG scheme, the electron beam distribution in the longitudinal phase space is manipulated first, by the interaction of the electrons with the seed laser in the modulator and later, by traversing the chicane. Finally, a harmonic of the seed laser wavelength is amplified in the radiator leading to fully coherent radiation.

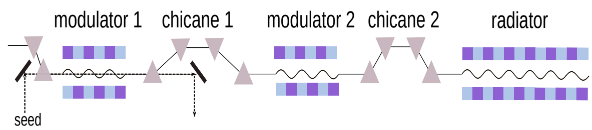
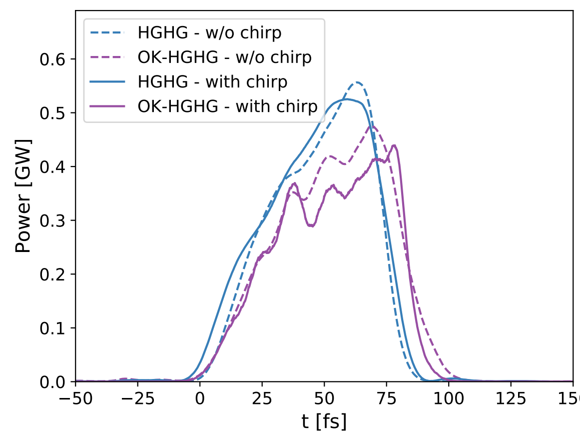


Figure 2: In the OK HGHG scheme, a harmonic of the seed laser wavelength is amplified in the radiator after a rather more complex manipulation of the electron beam distribution in the longitudinal phase that requires much lower seed laser power compared to the standard HGHG scheme of Figure 1.

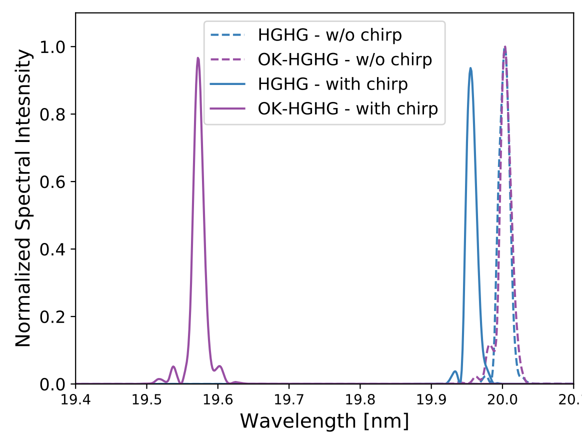
bunch with constant energy along it and we optimized the two schemes independently, initially, to get 8% bunching at the 15th harmonic of the seed laser wavelength upstream from the radiator and, eventually, to achieve good temporal and spectral properties of the output FEL pulse. While the two schemes required a different set of optimized parameters (see standard HGHG without chirp and OK HGHG without chirp in Table 2), the actual FEL pulses achieved with the two schemes are quite similar and can be directly compared in Fig. 3 (dashed lines are used for the simulation results with an electron beam without a chirp) and in Table 3, where the calculated properties of the output FEL pulses are listed. We notice that the pulse properties achieved with the OK HGHG are very similar to the standard HGHG in pulse energy, bandwidth, pulse duration and spectral intensity. It is worth highlighting that the OK HGHG scheme requires only 170 kW to achieve these results, while the standard HGHG scheme requires 61 MW seed laser peak power.

As a second step, we added a linear electron beam energy chirp of 40 m^{-1} (relative energy per unit length), corresponding to the energy chirp of the electron bunches anticipated in FLASH2020+ [15]. As expected from theory [16, 17], such a linear chirp causes a wavelength shift that depends on the longitudinal dispersion of the chicane, R_{56}. As the optical klystron scheme includes two chicanes with the first being rather strong for an HGHG scheme (see Table 2), it is expected that the overall wavelength shift in this scheme is more severe. This shift was confirmed in our simulations as shown in Fig. 3b with the solid lines. With the OK HGHG scheme the output wavelength shifted by 2.15% versus a 0.22% shift in standard HGHG.

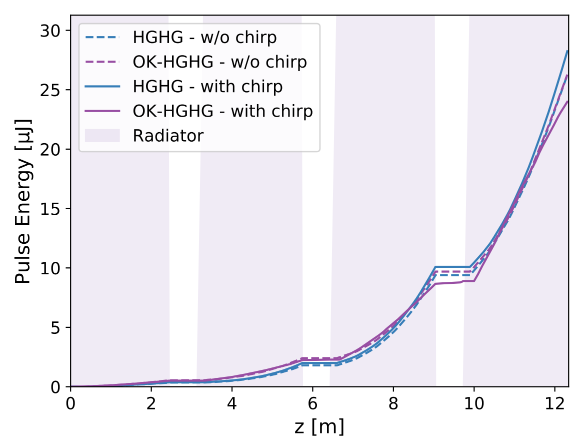
The standard HGHG scheme with a linear energy chirp was reoptimized by adjusting the radiator strength, K_{rad}, to



(a)



(b)



(c)

Figure 3: Output FEL radiation of a standard HGHG (blue lines) and an OK HGHG scheme (purple lines) without an energy chirp (dashed lines) and with a linear energy chirp h=40 m^{-1} (solid lines). In (a) we show the power profiles of the four optimized simulations, in (b) the spectra and in (c) the gain curves along the radiator.

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restore the resonance condition for the new shifted wavelength. This adjustment completely restored the FEL pulse properties as shown in Fig. 3 (comparing the blue solid and dashed lines) and Table 3. In a similar trend, in the optical klystron scheme with a linear energy chirp, the FEL pulse properties can be completely restored after optimization, as shown in Fig. 3 (comparing the purple solid and dashed lines) and Table 3. It should be noted that for the optical klystron scheme it was necessary to adjust the strength of modulator 2 as well, $K_{\mathrm{mod},2}$, to take into account the first wavelength shift occurring already after chicane 1.

Table 1: Simulation Parameters

Electron beam	
Energy	750 MeV
Uncorrelated energy spread	75 keV
Peak current	500 A (flat-top)
Seed laser	
Wavelength	300 nm
rms duration	33 fs (rms)

Table 2: Optimized Simulation Parameters for Standard and the Optical Klystron (OK) HGHG

Standard HGHG:	without chirp	with chirp
K_{mod}	5.42	5.42
P_{seed}	61 MW	61 MW
R_{56}	38.7 µm	38.7 µm
K_{rad}	1.792	1.786
OK HGHG:	without chirp	with chirp
rms $K_{\mathrm{mod},1/2}$	5.42/5.42	5.42/5.37
P_{seed}	170 kW	170 kW
$R_{56,1/2}$	482 µm/23.8 µm	482 µm/23.8 µm
rms K_{rad}	1.79	1.76

Table 3: Pulse properties of the output FEL radiation shown in Fig. 3 for a standard HGHG simulated with an electron bunch with and without a linear energy chirp, and an optical klystron (OK) HGHG simulated with an electron bunch with and without a linear energy chirp.

Standard HGHG:	without chirp	with chirp
Pulse energy	26.6 µJ	28.6 µJ
FWHM relative bandwidth	$8.7 \cdot 10^{-4}$	$7.5 \cdot 10^{-4}$
rms pulse duration	18.9 fs	20.7 fs
OK HGHG:	without chirp	with chirp
Pulse energy	26.6 µJ	24.2 µJ
FWHM relative bandwidth	$8.1 \cdot 10^{-4}$	$7.9 \cdot 10^{-4}$
rms pulse duration	22.2 fs	21.5 fs

CONCLUSION

In this proceeding, we investigated the benefits of the addition of an optical klystron in a standard HGHG scheme with detailed simulations. As a first step, we showed that FEL pulses of very similar properties can be generated with the standard HGHG scheme and the OK HGHG scheme of Fig. 1 and 2, respectively. When an electron beam with negligible energy chirp is considered, fully coherent radiation at 20 nm (the 15th harmonic of a 300 nm) was generated with only 170 kW in an OK HGHG, while the standard HGHG scheme requires a factor of almost 360 times higher peak power at 61 MW to achieve similar output FEL pulses. In addition, we verified the responses of the two schemes when a linear electron beam energy chirp ($h = 40\,\mathrm{m}^{-1}$) is incorporated into the simulations. It turns out that it is possible to completely recover the properties of the FEL radiation by properly optimizing the simulations in which the chirp is included. As expected, the energy chirp results in a known and predictable wavelength shift while the FEL properties, such as spectral intensity, pulse energy and peak power, do not suffer from this. These results bring us closer to a deeper understanding of the different optimization paths required by the two schemes and prove that the optical klystron scheme does not prevent us from exploiting electron beams with a linear energy chirp while it still makes use of a considerably lower seed laser power. It should be noted that the layout of the OK HGHG scheme, shown in Fig. 2, is identical to the one of echo-enabled harmonic generation (EEHG) [18] and therefore, facilities aiming at operation with EEHG, such as FERMI [19] and FLASH2020+ [14], can immediately take advantage of it without further modifications.

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