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IMPACT OF ELECTRON BEAM ENERGY CHIRP ON SEEDED FELS

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Abstract

Seeded FELs enable the generation of fully coherent, transform-limited and high brightness FEL pulses, as the start-up process is driven by an external coherent light pulse. During the design process of such FELs, it is important to choose carefully the electron beam parameters to guarantee high performance. One of those parameters is the electron beam energy chirp. In this contribution, we show simulation results and we discuss how the electron beam energy chirp affects the final spectrum.

INTRODUCTION

It is a quite common choice to study seeding techniques with an electron beam that has a relatively constant current, as far as this can be realistic, and is unchirped with a temporally constant energy. An energy chirp would possibly degrade the performance of the FEL since it might affect the density modulation efficiency and in addition, it shifts the central wavelength of the output radiation [1]. At the same time, in SASE FELs, it has been shown that a slightly positive chirp may be beneficial [2]. In seeded FELs, the energy chirp has already been proposed as a method to distinguish the signal of Echo-Enabled Harmonic Generation (EEHG) from High-gain Harmonic Generation (HGHG) for low harmonics [3], and as a method to produce two-color lasing as well [4]. In addition, it can be used as an FEL-chirp control technique [5, 6], since there is a correlation between the energy of the electron beam and the frequency of the FEL pulse that is defined through the resonance condition. Finally, the performance of EEHG with a chirped electron beam has been evaluated [7] for future designs.

In this contribution, we study the impact of a linear electron beam energy chirp of variable amplitude and sign on the HGHG-seeded FEL. More specifically, the wavelength shift and the impact on intensity and bandwidth are discussed and presented with simulation results. The optimum working points are determined and their stability is compared under an electron beam energy jitter and timing jitter study.

IMPACT ON HGHG

Wavelength Shift

The essential components for HGHG are a modulator in which the seed laser interacts with the electron beam and induces electron beam energy modulation, a dispersive section in which the energy modulation is converted into density modulation and a radiator that is resonant with the wavelength of the wanted harmonic of the seed laser [8]. For a better understanding of the effect of an energy chirp on the dispersive section that is used for the creation of density modulation in HGHG, it is useful to recall the process of bunch compressors. Bunch compressors (BCs) are sections with longitudinal dispersion R_{56} that are used to compress an electron beam temporally, usually to achieve a higher peak current and shorter FEL pulses. For an effective compression, the electron beam needs to travel in the dispersive section with, for instance, a linear energy chirp $h = \frac{dE}{ds}\frac{1}{E}$. This can be expressed mathematically as:

$$\delta = \delta_0 + hs_i + h's_i^2 + O(s^3),$$

where δ the is the relative energy offset, δ_0 represents the uncorrelated energy offset, s_i is the initial longitudinal intrabunch coordinate within the bunch and $h' = \frac{d^2E}{ds^2}\frac{1}{E}$. A chirp with a positive sign represents an electron bunch with a head of higher energy and a tail of lower energy. In this contribution, we restrict ourselves to a linear energy chirp h. An electron of an energy offset δ would exit a BC of a longitudinal dispersion R_{56} with a new longitudinal coordinate [9]:

$$s_f = s_i + R_{56}\delta = s_i(1 + hR_{56}) + R_{56}\delta_0.$$

Therefore, after differentiating, we get the linear compression factor:

$$C_{BC} = \frac{ds_i}{ds_f} = (1 + h \cdot R_{56})^{-1}. \qquad (1)$$

In the case of HGHG, the dispersive section converts the energy modulation to density modulation by forming microbunches with a longitudinal periodicity that is equal to the wavelength of the seed laser. However, if the electron beam is chirped, the periodicity will be affected by the compression/decompression that takes place due to Eq. (1). This is illustrated schematically in Fig. 1. The compression factor of the wavelength of the FEL radiation would be [10]:

$$C_{HGHG} = \frac{\lambda_{HGHG}}{\lambda'_{HGHG}} = (1 + H \cdot B)^{-1}, \qquad (2)$$

where $H \cdot B \propto h \cdot R_{56}$ [10]. This result is analogous to the derived formula of Eq. (1) for bunch compression.

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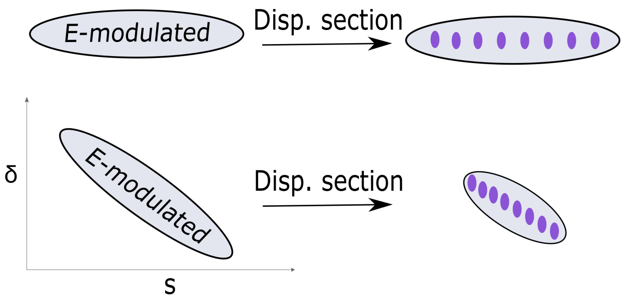

Figure 1: Impact of a dispersive section on the longitudinal phase space distribution of an energy modulated electron beam. In both cases, microbunches are formed. However, when the energy-modulated electron beam is chirped, the distance between the microbunches is altered.

SIMULATION RESULTS

sFLASH [11] is an experiment at FLASH in Hamburg and it is dedicated to seeding development study. The simulations were performed with Genesis 1.3 [12] version 4 in a time-dependent mode using typical sFLASH parameters, shown in Table 1.

Table 1: Simulation Parameters

Electron beam	
Energy	685 MeV
Uncorrelated energy spread	50 keV
Peak current	500 A (Gaussian)
Bunch length	60 µm (rms)
Seed laser	
Wavelength	266 nm
Peak Power	40 MW (Gaussian)
Laser pulse length	20 µm (rms)

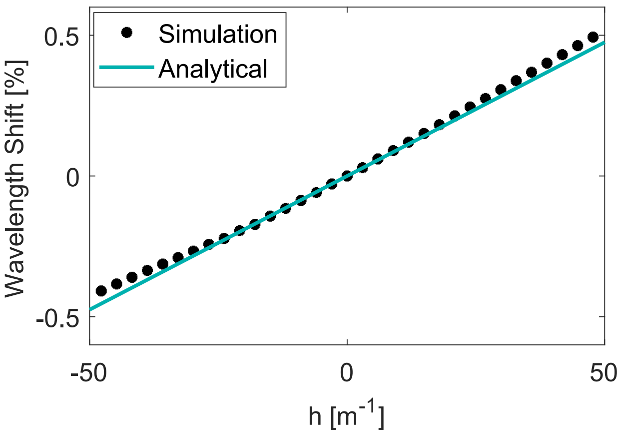

Figure 2: Impact of a linear energy chirp on the central wavelength of the output FEL spectrum of HGHG.

In Fig. 2 the effect of a linear energy chirp on the the final wavelength is shown. The simulated results of the final FEL spectrum are compared to the analytical estimation (Eq.2).

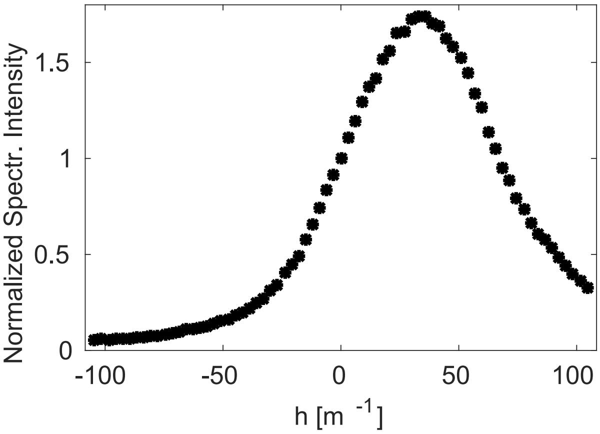

Figure 3: Impact of the electron beam energy chirp on the peak spectral intensity of the output spectrum. The intensity is normalized to the one of the unchirped electron beam. The $h = 0\,\mathrm{m}^{-1}$ is defined with the resonance condition.

According to Fig. 3, a peak spectral intensity is reached for a positive chirp of $33\,\mathrm{m}^{-1}$. However, one should notice that the peak spectral intensity can be optimized by optimizing the undulator parameter K of the radiator for each chirp to achieve optimal performance. In the simulations presented in this paper, we have used the undulator parameter calculated with the resonance condition for the nominal energy. Unlike the wavelength shift, the behaviour of the intensity is not symmetric for different signs of chirps, with a clear preference in positive chirps.

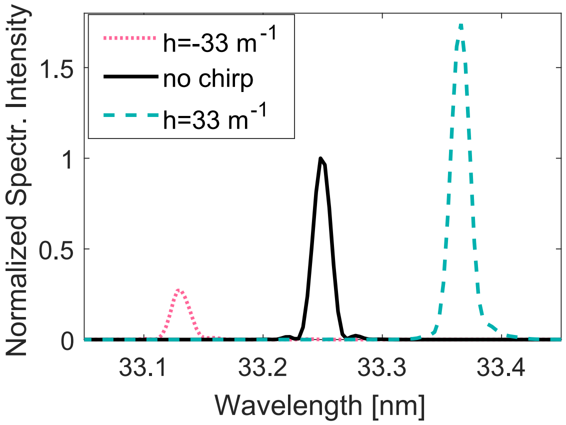

Figure 4: Impact of an initial electron beam energy chirp on the output spectrum in comparison with the spectrum generated with an unchirped electron beam. The intensity is normalized to the one of the unchirped electron beam.

For selected chirps out of this scan, the output spectra are shown in Fig. 4. The calculated bandwidth is not varying significantly, with the positive-chirped electron beam having less than 1% broader bandwidth and the negative-chirped electron beam having roughly 7.7% broader bandwidth than the unchirped case. The FWHM bandwidth of unchirped electron beam is $4.41 \cdot 10^{-4}$. In the same figure, one can see the wavelength shift as well.

Jitter Study

Additional simulations were performed to investigate whether the performance of chirped electron beams is sensitive to electron beam energy jitter and timing jitter between the seed laser and the electron beam. For the simulations we assumed a maximum timing offset of ±100 fs and a maximum beam energy offset of ±0.2%. The working points which are studied and compared are 1) with an unchirped electron beam and 2) with a chirp of $33\,\mathrm{m}^{-1}$.

Timing jitter In Fig. 5 the timing jitter sensitivity of the two different working points is shown. It is concluded that an electron beam with an energy chirp leads to a peak spectral intensity which is more stable to timing jitter within a small range of jitter (±20 fs). However, for larger deviations (more than ±50 fs) the unchirped electron beam is affected less by the jitter. In both cases, we have optimal performance for the nominal case in which the peak current of the electron beam overlaps longitudinally with the peak power of the seed laser in the middle of the modulator. Finally, we notice that both curves are asymmetric; the unchirped electron beam has a better performance in terms of peak spectral intensity when the seed laser is falling behind, than when it is ahead compared to the nominal case. The chirped electron beam leads to increased spectral intensity for positive timing offset, which means that the seed laser is energy-modulating a part of the electron beam that has higher than the nominal energy.

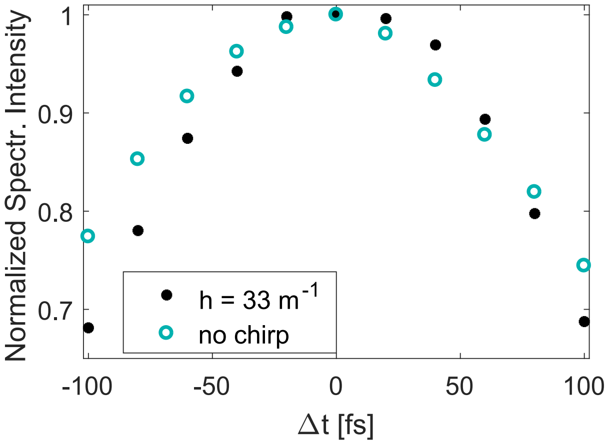

Figure 5: Impact of timing jitter on the intensity of the output spectrum for a chirped and an unchirped electron beam. We assume that for $\Delta t = 0$ the peak current of the electron beam overlaps with the peak power of the seed laser in the middle of the modulator. The intensity is normalized the maximum intensity for each chirp.

Electron beam energy jitter The energy jitter was simulated as a constant additional term applied to all particles over the electron bunch (see Fig. 6). Similarly to the timing jitter, for small deviations the chirped electron beam seems to be more stable and for larger deviations, the unchirped electron beam is lead to considerably lower performance. It should be noted that by fine-tuning the undulator parameter of the radiator one can optimize each working point, therefore we are only interested in the stability of these working points.

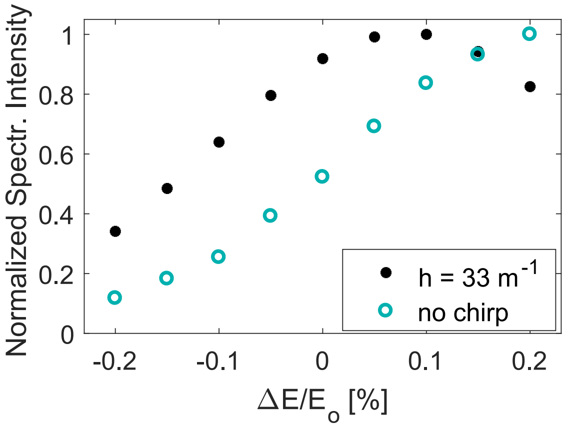

Figure 6: Impact of energy jitter on the peak intensity of the output spectrum for a chirped and an unchirped electron beam. We assume that for $\Delta E/E_o = 0$ the energy is the nominal one. The intensity is normalized to the maximum one for each chirp.

DISCUSSION

It was shown that the effect of energy chirp for HGHG is mainly imprinted as a wavelength shift and as an intensity increase/decrease, while the impact on the bandwidth is negligible on the selected spectra studied. It was observed in the simulations that the optimum intensity is appearing for a chirp $h = 33\,\mathrm{m}^{-1}$ with which one can gain in peak spectral intensity. A fine tuning of the resonant wavelength of the radiator can increase the performance of the working points simulated here. The timing jitter and the electron beam energy jitter study showed that the chirped electron beam that was studied offers more stability in the output spectrum for small jitter ranges in terms of peak spectral intensity. However, one should take into account that this advantage is coming with a shifted in wavelength spectrum. It is concluded that given the needs and the goals of an HGHG experiment one can use chirped electron beams as well without sacrificing the performance of the FEL if the wavelength shift can be tolerated. Finally, for the simulated setup a positive chirp is preferable.

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