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Control of FEL radiation properties by tailoring the seed pulses

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Abstract. Seeded free-electron lasers (FELs) produce intense, ultrashort and fully coherent X-ray pulses. These seeded FEL pulses depend on the initial seed properties. Therefore, controlling the seed laser allows tailoring the FEL radiation for phase-sensitive experiments. In this contribution, we present detailed simulation studies to characterize the FEL process and to predict the operation performance of seeded pulses. In addition, we show experimental data on the temporal characterization of the seeded FEL pulses performed at the sFLASH experiment in Hamburg.

1. Introduction

At FLASH, a soft x-ray FEL user facility at DESY in Hamburg, an experimental setup for seeding developments, sFLASH, was installed upstream of the FLASH main SASE undulator in 2010[1]. The setup is operated in a high-gain harmonic generation (HGHG) scheme [2] and also the scheme of echo-enabled harmonic generation (EEHG) is possible and currently under study [3]. All the results presented here are obtained using the consolidated HGHG scheme. In this scheme, the seed laser pulse interacts with an electron bunch in an undulator (modulator) producing a sinusoidal modulation of the electron energy and a dispersive section converts it into density modulation. The distance between the density spikes is defined by the laser wavelength. For a seed laser pulse with a time-dependent wavelength (chirp), we expect that also the spike separation is not uniform along the electron bunch which results in a widening of the final FEL bandwidth as described in [4]. To gain more knowledge on the seed laser chirp, the final FEL pulse characteristics can be studied. In fact, the chirp developed by the FEL radiation is dependent on the electron energy chirp, the seed laser chirp, and the FEL process itself[5]. With the assumption that the electron bunch has no relevant chirp and that the chirp introduced by the FEL amplification process in the short radiator (10 m long) has a negligible effect, the seed laser chirp is directly correlated with the FEL chirp.

The FEL pulse duration coming from sFLASH FEL can be measured in an experimental hutch in which a setup for THz streaking is located [7, 6]. In the following, results from this experiment are presented and compared to a set of simulations under variation of the chirp in the seed laser.

2. Laser pulse generation and characterization

The 267-nm UV seed pulses are generated in a third-harmonic generation (THG) process from a near-infrared (NIR) Ti:sapphire laser pulse at a repetition rate of 10 Hz. Already after the THG setup, the seed laser pulses are not Fourier-transform-limited, meaning that a chirp in the temporal phase is introduced due to the various dispersive media of the optical setup. Since the setup is not in vacuum, the pulses have to pass through a first vacuum quartz window of 3 mm thickness that separates the laboratory atmosphere from the high-vacuum beam tube (10^{-6} mbar) containing mirrors to transport the seed into the FEL tunnel. Here, a 1-mm fused-silica vacuum window permits the passage of the seed pulses into machine vacuum. The vacuum windows further increase the amount of the seed laser chirp. The current setup does not allow to measure the chirp directly at the modulator. Nevertheless, we can characterize the spectrum and duration of the seed laser pulses immediately after the THG setup in the laboratory using a commercial spectrometer (Ocean Optics HR4000) with 1 nm-resolution and a cross-correlation measurement. A bandwidth of $\Delta\lambda_{\text{seed}} = (1.3 \pm 0.5)$ nm FWHM (corresponding to an RMS spectral width of $\sigma_{\omega,\text{seed}} = (14.7 \pm 0.3)$ THz) was estimated averaging over several UV spectrum measurements. Additionally, a pulse duration of $\sigma_{t,\text{seed}} = (140 \pm 10)$ fs RMS is obtained from the cross-correlation measurement. This pulse has time-bandwidth product $\sigma_{\omega,\text{seed}} \cdot \sigma_{t,\text{seed}} \simeq 2.1$, while for a Fourier-transform-limited Gaussian pulse the time bandwidth product is $\sigma_\omega \cdot \sigma_t = 1/2$, therefore it is confirmed that it is not Fourier-transform-limited. The chirp parameter at this point is obtained using the relation [8]

$$\sigma_t \cdot \sigma_\omega = \frac{1}{2}\sqrt{1 + (2\sigma_t^2\alpha)^2}\ , \tag{1}$$

where $\alpha_{\text{seed}} = \partial^2\phi_{\text{seed}}/\partial t^2 = (102 \pm 8)$ THz/ps with $\phi_{\text{seed}}(t)$ being the phase of the seed laser pulse. From α, we can derive the group delay dispersion (GDD) of the seed laser pulses

$$GDD \cdot \sigma_\omega^2 = \alpha \cdot \sigma_t^2\ , \tag{2}$$

resulting in $GDD_{\text{seed}} = (9.2 \pm 0.7) \cdot 10^3$ fs^2.

3. Simulation of seeded FEL

The simulation of the seeded FEL is conducted in two sequential runs of the code GENESIS [9]. In the first run, the laser-electron interaction in the six-period modulator is simulated. The chosen parameters for the electron beam have typical values used during the seeding experiments at sFLASH, the bunch is assumed to have a Gaussian profile with a peak current at $I = 500$ A and RMS duration 96 μm. The electron energy is 685 MeV and the energy spread is 67 keV. The transverse size of electron beam is chosen to be completely covered by the transverse profile of the seed laser beam. For the seed laser pulse a Gaussian beam profile was assumed

$$P_{\text{seed}}(t) = P_0 \exp\left(-\frac{(t-t_0)^2}{2\sigma_{t,\text{seed}}^2}\right). \tag{3}$$

Here, $P_0 = E_{\text{seed}}/(\sqrt{2\pi}\sigma_{t,\text{seed}})$ is the peak power of the seed laser pulse at time t_0 given by the total pulse energy E_{seed} that was set to a value of 16.5 μJ for the simulations assuming a pure TEM_{00} mode. Consequently, as a bigger chirp leads to a longer time duration at constant bandwidth, the peak power decreases.

The temporal phase of the seed laser pulse is

$$\phi_{\text{seed}}(t) = -\frac{\alpha}{2}(t-t_0)^2 + \omega_0(t-t_0) + \phi_0, \tag{4}$$

where α is the chirp value described above, describing the variation of the angular frequency in time $\omega(t) = d\phi_{\text{seed}}(t)/dt = -\alpha(t-t_0) + \omega_0$. In GENESIS, the linear term of the phase is already implemented, only the quadratic term needs to be specified.

Figure 1 shows the analytical curve describing the dependence of the chirp α on the GDD. The point with zero GDD and zero chirp is the case of a Fourier-transform-limited pulse with a minimum RMS duration of $\sigma_{t,\text{seed}} = 31.4$ fs at $\Delta\lambda = (1.3 \pm 0.5)$ nm bandwidth.

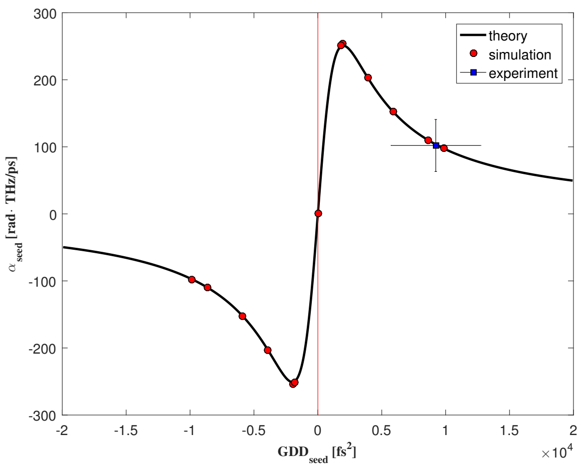

Figure 1. Chirp parameter α of the seed laser pulse as a function of the group delay dispersion (GDD) at the entrance of the modulator. The black line shows the theoretical relation between α and the GDD and red squares show the simulated points, for these points the α_{seed} is the value of the chirp immediately before the modulator. The blue point represents the chirp value of the seed laser measured immediately after the THG setup (thus the dispersion added from the vacuum windows in between is not included) before the THz streaking experiment. The orange vertical line separates the region with negative GDD (anomalous dispersion, red comes first) from the region with positive GDD (normal dispersion, blue comes first).

In the second GENESIS run, the electron bunch goes through the magnetic chicane and afterwards radiates inside a radiator section of three undulators with 60 periods and a fourth with 120 periods tuned to the eighth harmonic of the seed laser pulse for this study. The magnetic chicane longitudinal dispersion is optimized to achieve the maximum bunching (Eq. 5), that gives an optimal FEL performance by achieving saturation at the end of the radiator. This aspect is essential because FEL saturation before the end of the radiator would result in deterioration of the Gaussian time profile.
The knobs that could be touched in this procedure are the parameters controlling the bunching factor [2]

$$b_n = \exp\left(-\frac{1}{2}B^2 n^2\right) J_n(-nAB) \ , \tag{5}$$

where $A = \Delta\gamma/\sigma_\gamma$ is the energy modulation $\Delta\gamma$ imprinted by the seed laser pulse onto the electron beam normalized to the intrinsic energy spread of the electron bunch σ_γ. The other relevant parameter is $B = R_{56} k_l \sigma_\gamma / \gamma$, where the R_{56} is the longitudinal dispersion from the modulator to the radiator and J_n is the Bessel function of the first kind of order n (in the simulation study and in the experiment, the harmonic order n was 8).
In this case we do not want to change the properties of the seed laser pulse, because they are under study, so to optimize the FEL performance, the R_{56} parameter has been scanned and the

best FEL performance has been selected for the final simulation.

The final result contains information on the power profile of the seeded radiation. From Gaussian fits to the final temporal profile of the FEL pulse, we have extracted the RMS pulse duration and compared it with measured values using THz streaking [7] and the theoretical expectation [10].

4. Simulation result and comparison with experiment

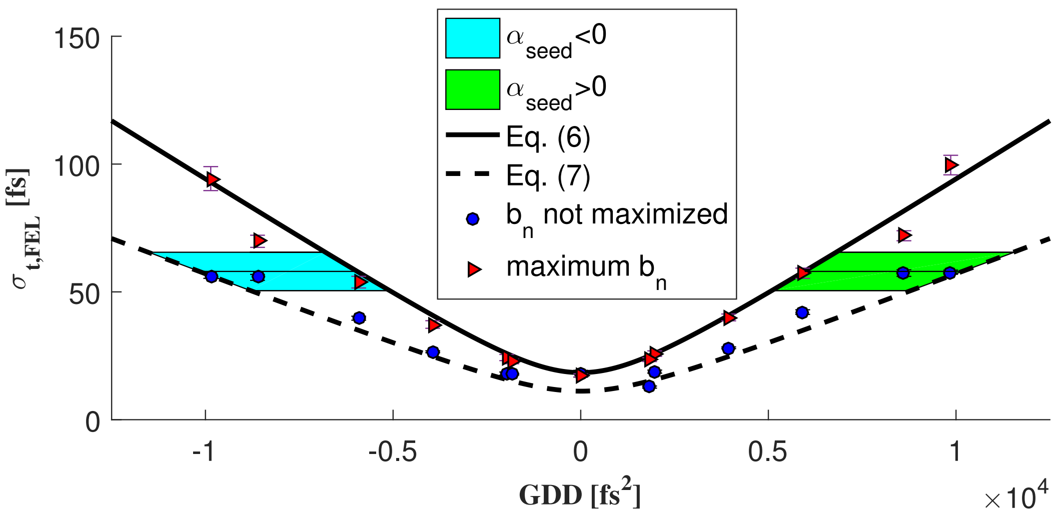

Figure 2. Duration of the seeded FEL pulses $\sigma_{t,\mathrm{FEL}}$ as a function of the GDD of the seed laser pulse GDD_{seed}. The color-filled boxes represent the regions where the experimental point was measured from the THz streaking experiment. These boxes are limited vertically from error bars given by the experimental uncertainty and the horizontally from the two theoretical curves. The measured time duration of the FEL pulse permits to retrive the initial GDD of the seed laser pulse at the beginning of the modulator. The markers represent the FEL performance foreseen from the simulations: red triangles show the case of optimized bunching and the blue circles show the case with small dispersion, so low bunching factor.

4.1. Experimental result

At the FEL seeding experiment sFLASH, a THz streaking setup is installed [7]. Using these unique photon diagnostic capabilities, the seeded FEL pulses were found to have an RMS duration of $\sigma_{t,\mathrm{FEL}} = (58 \pm 7.5)$ fs. and chirp $\alpha_{FEL} = (970 \pm 400)$ THz/ps [1].

4.2. Theoretical expectations

Based on the analytical calculations in [11], the FEL pulse length with optimized bunching is [10]

$$\sigma_{t,\mathrm{FEL}} \sim \frac{7}{6}\frac{\sigma_{t,\mathrm{seed}}}{\sqrt[3]{n}} \,. \tag{6}$$

That means that the dispersion R_{56} and the energy modulation from the seed laser $\Delta\gamma$ gives a bunching that permit the FEL pulse to reach saturation at the end of the radiator, without

[1] In the paper [7], the chirp is defined as $c = -2\alpha$

degradation of the pulse, like pulse splitting. The duration of the FEL pulse decreases if the seed power and the dispersion R_{56} are decreased. In [11] the duration of the FEL pulse in this case is given by

$$\sigma_{t,\mathrm{FEL}} = \frac{\sigma_{t,\mathrm{seed}}}{\sqrt{n}} \ . \tag{7}$$

4.3. Simulation result

The calculated FEL RMS pulse durations $\sigma_{t,\mathrm{FEL}}$ are reported in Fig. 2 as a function of the initial GDD of the seed laser GDD_{seed}. In the same plot, the two theoretical curves (Eqs. 6 and 7) confine the region in which the simulated points are expected. Finally, the cyan and green regions represent the temporal duration of the FEL pulses measured in the THz streaking experiment within the measurement error. According to this analysis, GDD_{seed} during the experiment was confined to the value $(8.3 \pm 3.2) \cdot 10^3$ fs^2. According to Fig. 1 results that the chirp α_{seed} is (127 ± 43) THz/ps. Accordingly with simulations, the sign of the seed laser pulse chirp is kept during the FEL process, thus the green region in Fig. 2 describes the seed laser (because the measured chirp of the FEL is positive).

The points $\sigma_{t,\mathrm{FEL}}$ indicated with triangular marker that are greater compared to the behavior foreseen from Eq. 6 represent the cases in which the electron bunch was slightly overbunched. While the points that are smaller represent cases in which the bunching was not fully optimized. To correct the overbunching it would be necessary to set a lower dispersion parameter, while for the other points the dispersion should be increased.

5. Conclusion and outlook

Numerical simulations of an FEL seeded with chirped UV pulses were conducted. The time duration of the FEL pulses is in agreement with theoretical expectations and in particular with the experimental FEL duration derived from the THz streaking measurement. This has allowed to derive a possible value of the GDD and chirp of the seed pulses at the modulator even though direct diagnostics are missing at the moment. The installation of a spectrometer and cross-correlator in tunnel before the modulator would permit to measure and compare the chirp of the seed laser with the value estimated from the simulation results presented.

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