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MEASUREMENT OF THE LASER-INDUCED ENERGY MODULATION AMPLITUDE AT THE SHORT-PULSE FACILITY AT DELTA*

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Abstract

The short-pulse facility at the synchrotron light source DELTA operated by the TU Dortmund University employs coherent harmonic generation (CHG) to provide ultrashort pulses in the vacuum ultraviolet and terahertz regime. Here, a laser-electron interaction results in a modulation of the electron energy which is transformed into a density modulation by a magnetic chicane. Measurements of the energy modulation amplitude with different techniques including an RF phase modulation are presented. A combination of the results allow to estimate the energy spread of the electron beam.

INTRODUCTION

The short-pulse facility at the 1.5-GeV synchrotron light source DELTA operated by the TU Dortmund University produces ultrashort light pulses in the visible and vacuum ultraviolet (VUV) regime by employing the coherent harmonic generation (CHG) technique [1]. Based on an interaction of a femtosecond laser pulse with a single electron bunch, a sinusoidal modulation of the electron energy results in the coherent emission of synchrotron radiation pulses at harmonics of the laser wavelength while preserving the pulse duration of the laser pulse.

In the CHG scheme (see Fig. 1, top), an interaction of an electron bunch in an undulator ('modulator') with a co-propagating laser pulse leads to a sinusoidal modulation of the electron energy E with an amplitude ΔE. Subsequently, the energy-dependent path length differences

$$\Delta z = r_{56} \frac{\Delta E}{E} \tag{1}$$

in a magnetic chicane with strength r_{56} transforms the energy modulation into periodic microbunches at intervals of the laser wavelength λ_L. The degree of microbunching is described by the so-called bunching factor [2]

$$b_n = e^{-\frac{1}{2}n^2 B^2} \cdot J_n(n \cdot A \cdot B), \tag{2}$$

with

$$A = \frac{\Delta E}{\sigma_E} \quad \text{and} \quad B = r_{56} \cdot \frac{2\pi}{\lambda_L} \cdot \frac{\sigma_E}{E}.$$

Here, n is the harmonic number, J_n is the bessel function of the order of n, and σ_E is the natural energy spread of the electron bunch. With a properly set chicane strength r_{56}, the bunching factor is maximized and can be described by [3]

$$b_n \approx \frac{0.68}{n^{1/3}} \exp\left(-\frac{n^2}{2A^2}\right). \tag{3}$$

In the following undulator ('radiator'), the microbunches give rise to coherent emission of synchrotron radiation at harmonics of the laser wavelength with an emitted power

$$P_{coh} \propto N^2 \cdot b_n^2. \tag{4}$$

scaling quadratically with the number of electrons N. Since only electrons interacting with the laser pulse contribute to the bunching factor, the duration of the coherently emitted pulses is of the order of the laser pulse duration and, thus, in the tens of femtosecond range.

Further downstream, the energy-modulated electrons leave their original position within the electron bunch due to energy-dependent path length differences in the following dipoles, thereby forming a dip in the longitudinal electron density. This dip with a width in the sub-ps range gives rise to coherent emission of THz radiation pulses.

As given in Eq. (3), the bunching factor scales with e^{-n^2} which practically limits the CHG scheme to about $n = 5$. In 2009, the more sophisticated technique echo-enabled harmonic generation (EEHG) [4] was proposed (see Fig. 1,

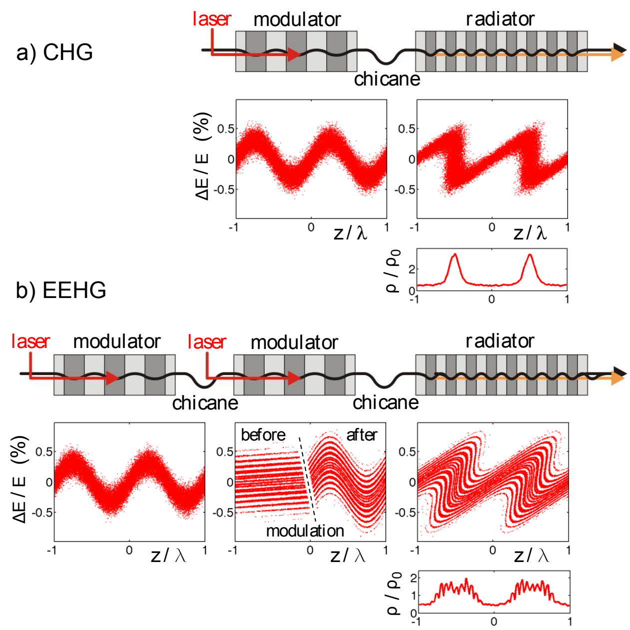

Figure 1: Magnetic setups for CHG (a) and EEHG (b), corresponding longitudinal phase space distributions and the final longitudinal charge density.

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bottom). Here, another modulator is added upstream of the CHG setup in which another laser-electron interaction takes place followed by a strong chicane. This results in a longitudinal electron distribution which allows for coherent emission at much higher harmonics as the bunching factor, here, scales with $n^{-1/3}$. Preparations for a modification of the short-pulse facility towards employing EEHG are in progress [5].

THE SHORT-PULSE FACILITY AT DELTA

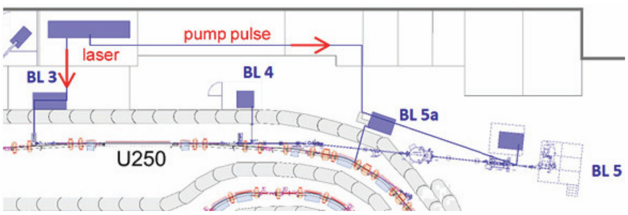

Figure 2: The short-pulse facility in the northern part of DELTA comprises a laser laboratory, the seeding beamline BL 3, the electromagnetic undulator U250, the diagnostics beamline BL 4, the VUV beamline BL 5, and the THz beamline BL 5a.

In 2011, the CHG scheme was implemented at the DELTA storage ring to generate ultrashort coherent synchrotron radiation pulses in the VUV regime [6,7]. In a laser laboratory, a titanium:sapphire laser system provides 800-nm seed pulses at a repetition rate of 1 kHz and up to 8 mJ pulse energy, which are focused and guided into the storage ring via beamline 3 (BL 3, see Fig. 2). The modulator, chicane and radiator are realized by dividing the undulator U250 into three independently powered sections. For diagnostics purposes, both, synchrotron radiation and laser pulses are guided via beamline BL 4 to a hutch equipped with screens, photodiodes and a streak camera used to establish the transverse and longitudinal overlap of the electron bunch and the laser pulse and, thus, to enable the emission of CHG pulses. For the characterization of CHG radiation see e.g. [8, 9].

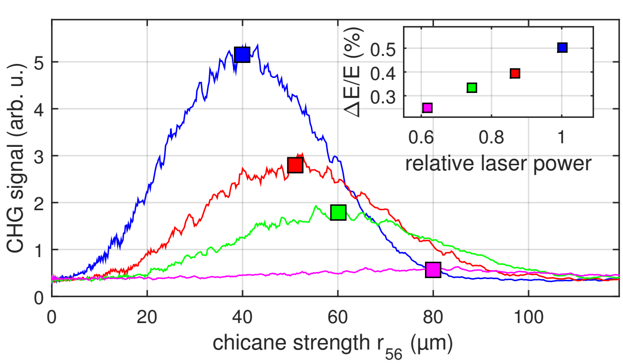

Figure 3: CHG signal versus chicane strength r_{56} for different laser pulse energies. Squares: Maximum signal. Top right: Corresponding relative modulation amplitudes $\Delta E/E$ for different laser pulse energies.

Pump-probe experiments using the ultrashort CHG pulses as probe pulse can be performed at the soft-X-ray beamline (BL 5). A fraction of the laser pulse with adjustable delay is directly guided to the experiment and is used as a pump pulse. A first demonstration of a pump-probe experiment was presented in [10].

The laser-induced THz radiation is picked up at a bending magnet using a dedicated THz beamline (BL 5a) and gives the first indication for a successful laser-electron overlap. Furthermore, several experiments utilizing the THz radiation were carried out (e.g. [11]).

EXPERIMENTAL RESULTS

Measuring the Energy Modulation Amplitude

For a certain energy modulation amplitude, the bunching factor given in Eq. (2) follows a Bessel function and reaches an optimum at a certain chicane strength r_{56}.

In Fig. 3, CHG signals while continuously increasing the chicane strength are shown for different laser pulse energies and, thus, different modulation amplitudes. With the argument of the Bessel function depending on $\Delta E/E$, the maxima of each curve allow to determine energy modulation amplitudes $\Delta E/E$ of up to 0.5% which are shown in the top right plot of Fig. 3.

CHG in the Presence of an RF Phase Modulation

In standard user operation at DELTA, a routinely applied phase modulation of the accelerating RF results in a decrease of the average electron density while increasing the beam lifetime [12]. In CHG operation, this would decrease the achievable signal.

However, different parameters of the RF phase modulation enables the formation of two stable islands rotating in the longitudinal phase space. Depending on the phase modulation amplitude, this results in either a periodic lengthening of the electron bunches (see Fig. 4, center), or the formation of two separate islands (Fig. 4, right).

In the regime of periodic lengthening, phases with longer bunch duration correspond to a reduced energy spread and vice versa. By introducing a factor s which transforms $\sigma_E \to \sigma_E/s$ and, thus, $A \to s \cdot A$, and $N \to N/s$ since both energy spread and bunch length and, thus, number of electrons interacting with the laser pulse are affected by the RF phase modulation, Eq. (3) transforms into

$$P_{coh} \propto \left(\frac{1}{sn^{1/3}} \exp\left(-\frac{n^2}{2s^2A^2} \right) \right)^2 . \qquad (5)$$

Evaluating this formula for the third harmonic ($n = 3$) with different modulation amplitudes A yields the plot shown in Fig. 5. For large A, the emitted power is largest at phases with a small s which corresponds to a larger electron density but also a larger energy spread. For smaller amplitudes, the behavior reverses. Here, a small energy spread is required instead. The THz signal, however, does not change its behavior, as it mainly requires a small energy spread. This also

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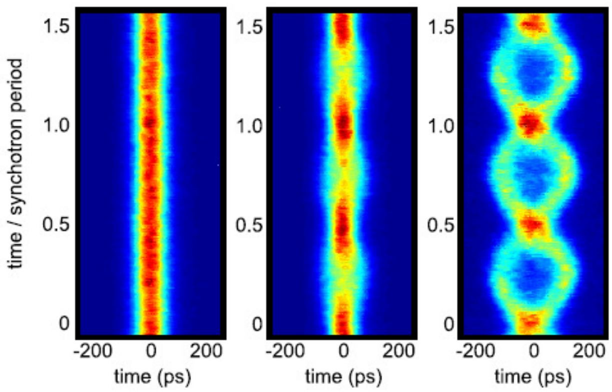

Figure 4: Streak camera images showing the evolution of the longitudinal bunch profile (horizontal axis) over 1.5 synchrotron periods (vertical axis) without RF phase modulation (left) and with RF phase modulation with increasing amplitude (center and right).

means that the THz and CHG signals are opposite in phase at large amplitudes and in-phase for smaller A (see Fig. 6 and also [13]).

In the intermediate region between large and small modulation amplitudes, for example at $A = 3.3$ (see Fig. 6), the CHG signals tends to oscillate twice as often. Here, a combination of reduced electron density but also reduced energy spread appears to be better than either a minimum energy spread or a maximum electron density.

Combining the measurement of the modulation amplitude $\Delta E/E$ by scanning the chicane strength r_{56} (see Fig. 3) with the determination of A as proposed here allows to estimate the energy spread σ_E of the electron beam.

In Fig. 6, the laser-induced THz and third-harmonic CHG signals are shown together with theoretical curves from Fig. 5. The modulation amplitudes correspond to those shown in Fig. 3. As expected, the signals are opposite in phase at a large energy modulation amplitude and being

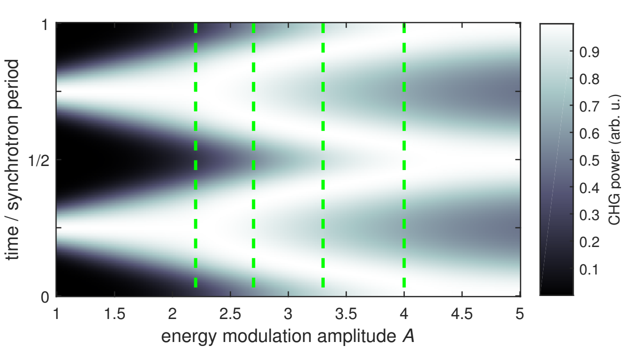

Figure 5: Normalized CHG power as function of the energy modulation amplitude A and time while s (see Eq. (5)) oscillates twice per synchrotron period due to RF phase modulation. Here, s oscillates between 0.7 and 1.3 and is smallest at $t = 0$. Curves used in Fig. 6 are indicated in green.

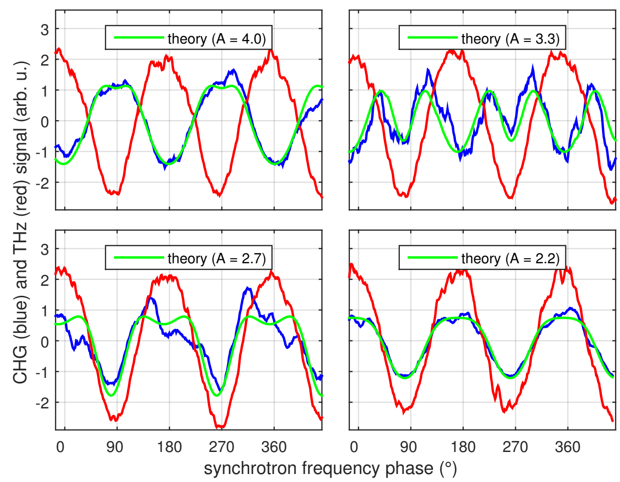

Figure 6: Laser-induced THz (red) and CHG (blue) signals (mean values subtracted) under the influence of an RF phase modulation versus the synchrotron frequency phase and theoretical CHG signals (green, from Fig. 5) for different energy modulation amplitudes A.

in-phase for a small amplitude. The two measurements in the intermediate regime with amplitudes of about $A = 3.3$ and $A = 2.7$ correspond to values of $\Delta E/E = 0.39\%$ and $\Delta E/E = 0.33\%$, both resulting in an estimated energy spread of $\sigma_E/E \approx 1.2 \cdot 10^{-3}$.

CONCLUSION AND OUTLOOK

With the implementation of CHG at DELTA, a modulation of the electron energy due to a laser-electron interaction allows the coherent emission of synchrotron radiation pulses at harmonics of the laser wavelength while maintaining the duration of the laser pulse. Measuring the energy modulation amplitudes $\Delta E/E$ and, using RF phase modulation, $\Delta E/\sigma_E$ allow to estimate the energy spread σ_E of the electron beam. A first result of $\sigma_E/E = 1.2 \cdot 10^{-3}$ is almost twice as high as the natural energy spread of $7 \cdot 10^{-4}$ according to the design lattice. A possible influence of the RF phase modulation on the energy spread requires further investigations.

In any case, the method will allow to detect changes of the energy spread caused, e.g., by insertion devices or collective effects.

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