SPECTRAL STUDIES OF ULTRASHORT AND COHERENT RADIATION PULSES AT THE DELTA STORAGE RING*

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Abstract

At the 1.5-GeV synchrotron light source DELTA operated by the TU Dortmund University, ultrashort and coherent radiation pulses in the VUV and THz regime are routinely generated by the interaction of electron bunches with femtosecond laser pulses. A laser-induced energy modulation is converted into a density modulation (microbunching) by a magnetic chicane, giving rise to coherent emission at harmonics of the initial laser pulses (coherent harmonic generation, CHG). As a first step towards active control of the shape and spectrum of CHG pulses, spectral studies were performed under variation of the chicane strength and the laser properties. The spectral phase of the laser pulses was controlled by tuning the laser compressor and monitored using FROG. A new autocorrelation method yields additional information on the pulse shape.

INTRODUCTION

Synchrotron radiation with short wavelengths is the standard tool to study the structure of matter on the atomic scale. However, synchrotron light pulses with durations of 30 to 100 ps (FWHM) are too long to temporally resolve atomic processes taking place on the sub-picosecond scale.

The need for radiation with short wavelength *and* short pulse duration has prompted new developments such as the free-electron laser (FEL) providing extremely brilliant short-wavelength radiation with femtosecond pulse duration. To date, only four linac-based FEL facilities at short wavelengths are in single-user operation (FLASH, LCLS, SACLA, and FERMI) while more than 50 synchrotron light sources worldwide [1] supply multiple beamlines simultaneously. It is therefore worthwhile to study methods which allow to generate shorter pulses at conventional synchrotron light sources. Some of these methods are borrowed from FEL seeding schemes in which the electric field of a femtosecond laser pulse modulates the energy of electrons within a short "slice" at the center of a longer electron bunch. In a scheme known as coherent harmonic generation (CHG, Fig. 1) [2], a magnetic chicane converts the energy modulation generated in an undulator ("modulator") into a density modulation (microbunching) giving rise to a short pulse of coherent radiation at harmonics of the laser wavelength in a second undulator ("radiator"). The power ratio between the short coherent and the long incoherent radiation component

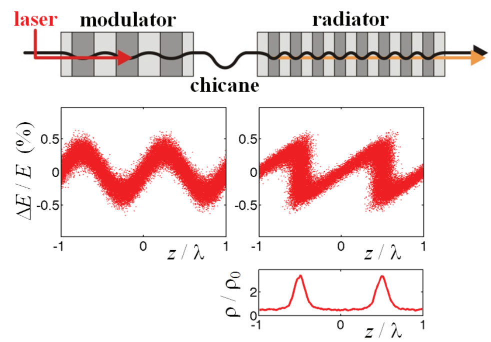

Figure 1: Sketch of the short-pulse scheme CHG with the electron distribution in phase space (relative energy deviation $\Delta E/E$ versus longitudinal coordinate z in units of the laser wavelength λ) and electron density $\rho(z/\lambda)$.

is given by

$$\frac{P_{\mathrm{short}}}{P_{\mathrm{long}}} = \frac{n_{\mathrm{short}}^2\, b_h^2}{n_{\mathrm{long}}}. \tag{1}$$

With a bunching factor of $b_h = 0.05$ for harmonic number h, $n_{\mathrm{long}} = 10^{10}$ electrons in the whole bunch and $n_{\mathrm{short}} = 10^7$ electrons in the slice, to give an example, the power ratio would be 25. In the CHG scheme, the bunching factor is given by [3]

$$b_h = 2e^{-h^2B^2/2}\,|J_h(hAB)|, \tag{2}$$

where $A = \Delta E_{\mathrm{max}}/\sigma_E$ is the energy modulation amplitude normalized to the rms energy spread, and $B \equiv r_{56}(2\pi/\lambda)(\sigma_E/E)$ is the dimensionless chicane parameter for a seed wavelength λ and a longitudinal displacement $\Delta z = r_{56}\Delta E/E$. However, Eq. 2 only holds for a constant modulation amplitude while, in reality, amplitude A follows the electric field distribution in the laser pulse, which can be assumed to be Gaussian in every coordinate. Thus, averaging over a 3-dimensional distribution $A(x, y, z)$ leads to an "effective" bunching factor. If the laser beam is wider than the electron beam, at least the longitudinal dependence $A(z)$ must be considered.

As shown in Fig. 2 for a maximum bunching factor $A_{\mathrm{max}} = 5$, the chicane parameter influences the CHG pulse shape. Maximizing the CHG intensity results in a single bell-shaped pulse (green), while increasing the chicane parameter causes two maxima with overbunching between them (blue) or even three maxima (magenta). As recently discussed in [4] for the case of FERMI, a seeded FEL near Trieste/Italy, this opens

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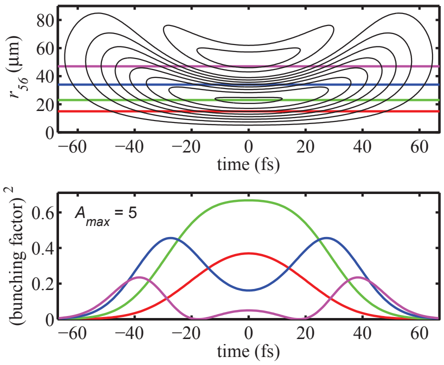

Figure 2: Top: Contours of equal bunching factor as function of longitudinal position (in time units) and chicane strength r_{56}. Bottom: Bunching factor squared as function of time along the colored lines in the top figure.

up the possibility of tailoring the pulse shape according to the user requirements.

If the pulse shape cannot be measured directly, which is usually the case for femtosecond pulses of arbitrary wavelength, it may be deduced from the spectrum. This, however, depends not only on the bunching factor at a given wavelength, but also on the wavelength distribution along the seed pulse. If a coherent seed pulse is not chirped, i.e., if its wavelength is uniform, the temporal pattern causes spectral fringes according to its Fourier transform. If, on the other hand, the seed pulse is strongly chirped, two successive maxima of the bunching factor not overlapping in wavelength would just lead to two maxima in the spectrum.

Observations similar to those discussed in [4] were made since 2013 with CHG radiation at the electron storage ring DELTA in Dortmund/Germany [5]. However, the interpretation of the spectra is not straightforward, as shown below, due to the nonlinear chirp of the seed pulses.

THE SHORT-PULSE FACILITY AT DELTA

The 1.5-GeV electron storage ring DELTA is operated as a synchrotron light source by the TU Dortmund University. In 2011, a short-pulse facility based on CHG was constructed to provide ultrashort coherent synchrotron radiation pulses in the VUV and THz regimes for users [6, 7]. The setup is shown in Fig. 2. Relevant parameters of the storage ring, the laser system, and the undulators are given in Table 1.

Seed pulses from a titanium:sapphire laser system are either focused directly through a beamline (BL 3) into the electromagnetic undulator U250 or are frequency-doubled first. The undulator, which usually supplies a beamline (BL 5) with soft-X-ray radiation, can be powered such that the 7 upstream/downstream periods act as modulator/radiator for the CHG scheme with a chicane between them. The energy modulation is performed at the full beam energy of 1.5 GeV during dedicated shifts, but was also tested during user operation (see Fig. 3).

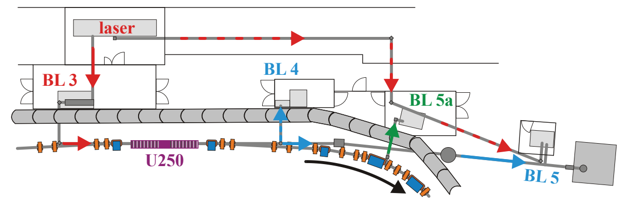

Figure 3: The short-pulse facility at DELTA comprising a laser system, a beamline (BL 3) sending seed pulses to the undulator U250, a diagnostics beamline (BL 4), a soft-x-ray beamline (BL 5), and a THz beamline (BL 5a).

A diagnostics beamline (BL 4) is used to observe the spatial overlap of laser and undulator radiation on screens and to establish the temporal overlap using a streak camera. Employing a Czerny-Turner-type spectrometer, spectra down to wavelengths of 190 nm are recorded by rotating a grating while measuring the radiation intensity with an avalanche photodiode. The pulse height is digitized, averaged and sent to the EPICS-based control system [8] by a digital oscilloscope. More recently, a second spectrometer was equipped with an image-intensified CCD (iCCD) camera [9]. Gating with minimum window of 2 ns allows to record spectra without the background of 2600 incoherent pulses (in single-bunch mode) between consecutive CHG pulses. Apart from much faster data acquisition (4 images per second compared to one grating scan over 8 minutes), the iCCD camera adds a new quality by allowing to obtain single-shot spectra.

Radiation at shorter wavelengths requires vacuum and is studied using a soft-X-ray beamline (BL 5) operated by the Forschungszentrum Jülich. Spectra are obtained by scanning

Table 1: Parameters of the DELTA Short-pulse Facility

electron storage ring	
beam energy	1.5 GeV
circumference	115.2 m
beam current (multibunch)	130 mA
beam current (single bunch)	20 mA
horizontal emittance	15 nm rad
relative energy spread	0.0007
bunch length (rms)	13 mm
titanium:sapphire laser system	
wavelength	800 nm
pulse energy @800 nm	8.0 mJ
pulse energy @400 nm	2.8 mJ
repetition rate	1 kHz
min. pulse duration (FWHM)	> 40 fs
undulators and chicane	
modulator/radiator period length	250 mm
number of modulator/radiator periods	7
undulator periods used as chicane	3
max. modulator/radiator K parameter	10.5
max. chicane R_{56} value	130 μm

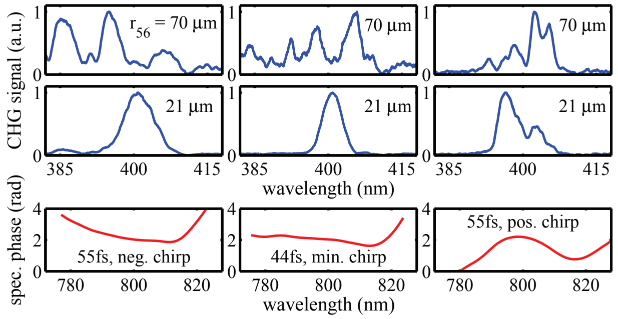

Figure 4: Spectral phase of 800-nm seed pulses (bottom) and CHG spectra at the second harmonic normalized to their maximum with the chicane set to r_{56} = 21 μm (center) and 70 μm (top). The measurements were performed with three different settings of the laser compressor. From left to right: negative chirp, shortest pulse, positive chirp.

a plane-grating monochromator and recording the photoelectron yield from a sample.

The short-pulse facility also comprises a dedicated beamline for terahertz (THz) radiation. The energy-dependent path length of off-energy electrons in the storage-ring lattice causes a sub-picosecond dip in the longitudinal electron distribution which gives rise to THz and sub-THz radiation over several turns [10]. See [11] for recent results.

SPECTRA OF CHG RADIATION

With seed wavelengths of 800 nm and 400 nm, CHG spectra were recorded at different harmonics under variation of the chicane strength, typically between r_{56} = 5 μm and 120 μm, to which a value of 10 μm for the longitudinal dispersion of the modulator must be added. The compression of the laser pulses after amplification was varied, resulting in typical pulse durations between 40 fs and 60 fs (FWHM). In the case of seeding with 800 nm, the temporal and spectral pulse properties were recorded using a FROG apparatus (frequency-resolved optical gating) [12]. However, air and the vacuum window on the way to the undulator may significantly modify these properties.

As an example, Fig. 4 shows spectra of second-harmonic CHG radiation while seeding with 800 nm pulses. As indicated by the spectral phase for three different compressor settings, the wavelength variation along the pulse is nonlinear. Otherwise, the spectral phase would be a parabola (or a straight line in the case of no chirp). For r_{56} = 70 μm, a CHG double pulse can be assumed and the spectra clearly exhibit interference fringes. Even at the lower r_{56} value, which corresponds to a single maximum of the bunching factor, the spectra are distorted by nonzero chirp. The interaction of chirped laser pulses including effects of the laser beam waist, wavefront curvature and Guoy phase (see e.g. [13]) was simulated using a self-written code. The resulting electron energy distribution was subjected to longitudinal dispersion and the bunching factor as function of wavelength was computed in 0.5-nm steps. In contrast to [4], the observed spectral

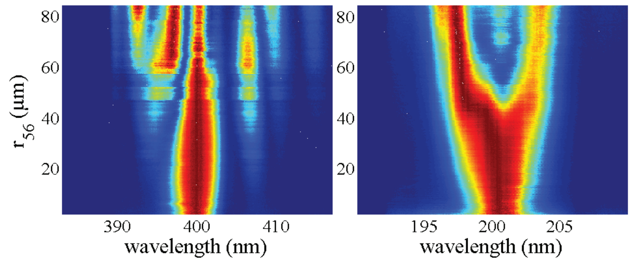

Figure 5: Sequence of 600 single-shot spectra of CHG radiation under slow variation of the chicane strength r_{56} while seeding with 800-nm (left) and 400-nm (right) laser pulses.

features are not reproduced under the assumption of a linear chirp. The next step will be to repeat the simulation with a seed pulse constructed from the measured spectral phase.

When seeding with 400-nm pulses, the laser compressor is usually tuned to maximize the power of the frequency-doubled pulses. In this case, the CHG spectra measured around 200 nm show a single peak at low r_{56} values and two peaks at higher chicane settings, as expected from seeding with a strongly chirped pulse. First measurements obtained using the iCCD camera are shown in Fig. 5. No equipment is available to directly characterize the 400-nm pulses, and since the second-harmonic generation is performed in air, the seed pulses will be chirped along their way through air and the vacuum window. Indirect evidence for the pulse shape comes from an autocorrelator-like measurement, in which modulator and radiator are both set to the seed wavelength, allowing for a twofold energy modulation with the seed pulse delayed by the chicane. While increasing the delay, a twofold modulation of the same electrons is indicated by oscillatory variations of the THz signal. In the test case shown in Fig. 6 with 800-nm seeding, the envelope of the THz oscillation amplitude resembles the pulse shape obtained by FROG, confirming the validity of the method.

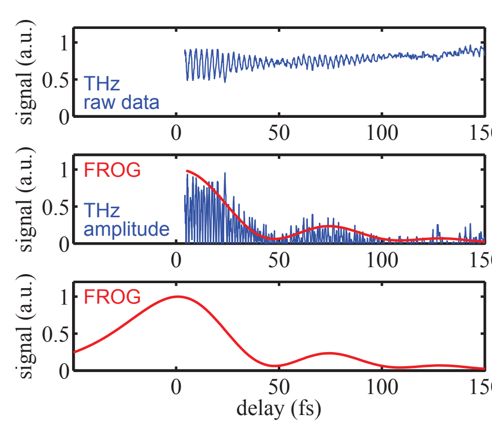

Figure 6: A high-cost low-resolution autocorrelator [14] for CHG seed pulses. A twofold energy modulation of the same electrons in two undulators is indicated by a periodic variation of the coherent THz signal (top). The amplitude of the variation (center) resembles the FROG result (bottom).

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