ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPWA022

CHARACTERIZATION AND OPTIMIZATION OF ULTRASHORT AND COHERENT VUV PULSES AT THE DELTA STORAGE RING*

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Abstract

At DELTA, a 1.5-GeV synchrotron light source operated by the TU Dortmund University, a source for coherent and ultrashort vacuum-ultraviolet (VUV) and terahertz (THz) pulses is now in operation. The VUV source is based on a laser-induced energy modulation and coherent harmonic generation (CHG). A subsequently developing dip in the longitudinal electron distribution gives rise to coherent THz radiation. Recent results regarding the optimization of the laser-electron interaction and characterization of the CHG pulses are presented.

INTRODUCTION

Synchrotron radiation with short wavelengths is the standard tool to study the structure of matter on the atomic level. However, synchrotron radiation pulses with a duration of 30 to 100 ps (FWHM) are too long to study dynamic processes such as chemical reactions, phase transitions, fast magnetic changes, etc. which take place on the sub-picosecond scale. The femtosecond regime, on the other hand, has been made available by mode-locked lasers at near-visible wavelengths which are not suitable to probe inner atomic shells or to provide spatial resolution on the atomic 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, 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 with brilliant and tunable radiation. It is therefore worthwhile to study methods which allow to generate shorter pulses at conventional synchrotron light sources.

SHORT-PULSE GENERATION

Some methods to generate sub-ps radiation pulses at storage rings are borrowed from FEL seeding schemes using a femtosecond laser pulse to modulate the energy of electrons within a short "slice" at the center of a long electron bunch. In a subsequent undulator, a short radiation pulse is emitted from the slice together with a long pulse from the rest of the bunch. Off-energy electrons are either transversely displaced in order to separate the short and long components of incoherent undulator radiation spatially ("femtoslicing" [2]) or a magnetic chicane may convert the energy modulation into a density modulation (microbunching) giving rise to a short pulse of coherent radiation at harmonics of the laser wavelength [3]. As long as the signal-to-background ratio

$$\frac{P_{\text{short}}}{P_{\text{long}}} = \frac{n_{\text{short}}^2\, b_h^2}{n_{\text{long}}} = f^2\, n_{\text{long}}\, b_h^2 \quad \text{with} \quad f \equiv \frac{n_{\text{short}}}{n_{\text{long}}} \qquad (1)$$

is tolerable, no geometric separation is required. Here, $f \approx 10^{-3}$ is the ratio between the number of electrons in the slice and in the bunch, and b_h is the bunching factor for harmonic number h. With $n_{\text{long}} = 10^{10}$, as an example, $b_h = 0.1$ would yield an excellent signal-to-background ratio of 10^2. This scheme is known as coherent harmonic generation (Fig. 1 a). Here, the bunching factor decreases with increasing harmonics as $b_h \sim \exp(-h^2)$. In contrast to that, echo-enabled harmonic generation (EEHG, Fig. 1 b) [4] involving a two-fold energy modulation is able to generate higher harmonics according to $b_h \sim h^{-1/3}$.

Further downstream along the storage ring, the energy-dependent electron path length leads to a dip in the longitudinal electron distribution giving rise to coherent THz radiation [5].

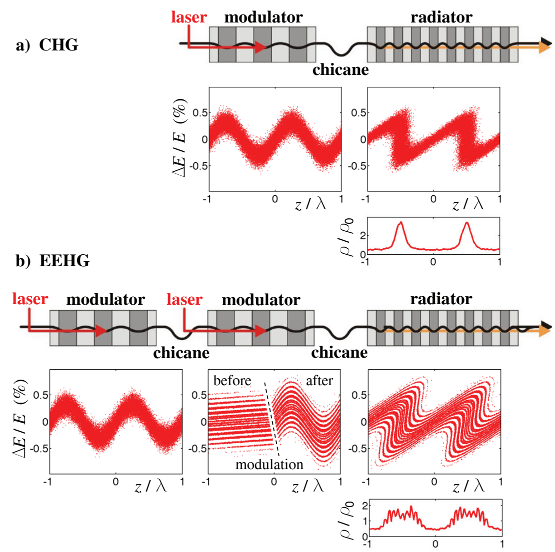

Figure 1: Short-pulse schemes a) CHG and b) EEHG with respective electron distributions in phase space (relative energy deviation $\Delta E/E$ versus longitudinal coordinate z in units of the laser wavelength λ) and electron density $\rho(z/\lambda)$.

* Work supported by BMBF (05K13PE3 and 05K13PEC), DFG (INST 212/236-1 FUGG) and the Land NRW.
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ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPWA022

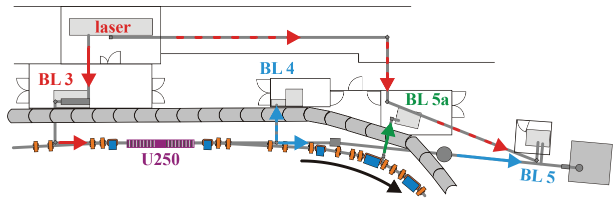

Figure 2: Short-pulse facility at DELTA comprising a laser system, the beamline BL 3 sending seed pulses to the undulator U250, the diagnostics beamline BL 4, the soft-x-ray beamline BL 5 and the THz beamline BL 5a.

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	3.0 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
synchrotron radiation beamlines	
diagnostics beamline (BL 4) range	1.5-6.4 eV
soft-x-ray beamline (BL 5) range	9-500 eV
terahertz beamline (BL 5a) range	0.4-29 meV

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]. Relevant parameters are listed in Tab. 1, the setup is shown in Fig. 2, .

A titanium:sapphire laser system provides ultrashort pulses at a wavelength of 800 nm which are either used directly for seeding or are frequency-doubled. The electromagnetic undulator U250, previously used as a storage-ring FEL [8], can be powered in optical-klystron configuration (undulator-chicane-undulator) and new power supplies allow to tune both 7-period undulators individually to a maximum wavelength of 800 nm at the full beam energy of 1.5 GeV. The three central periods of the U250 are used as a chicane with a maximum R_{56} value of 130 μm.

For a typical single-bunch current of 10 mA, the number of electrons is $n_{\rm long} = 2.4 \cdot 10^{10}$ and the fraction of contributing electrons f in Eq. 1 is below 10^{-3}. The energy-modulation amplitude is ultimately limited by the energy acceptance of $\Delta E_{\rm max}/E = 0.008$, given by the radiofrequency (RF) voltage. A planned upgrade of the RF system will shorten the bunches to 7 mm (rms), thus increasing f, and will also improve the energy acceptance.

At low harmonics, CHG with a signal-to-background ratio exceeding 10^2 is routinely observed [6]. The lowest CHG wavelength obtained so far with 400-nm seed pulses is 80 nm. In future, also frequency-tripling of the laser pulses is planned to reach a CHG wavelength of 53 nm (fifth harmonic of 267 nm). An already installed optical parametric amplifier will allow for variable seed and CHG wavelengths.

The diagnostics beamline BL 4 is used to establish the laser-electron interaction by observing the spatial overlap of laser and undulator radiation on screens and the temporal overlap with a streak camera. The beamline is also used to characterize CHG pulses in air down to a wavelength of 200 nm (6.4 eV). Fast detectors are required to avoid the background of incoherent radiation from 2600 turns between successive laser pulses. For intensity measurements, an avalanche photodiode is used while for spatially resolving studies (angular distribution, interference patterns etc.), an image-intensified CCD camera with a gate $\geq$ 2 ns is available. Radiation at wavelengths of 133 nm (9 eV) and below is studied using the soft-x-ray beamline BL 5. To bridge the wavelength gap between the two beamlines, it is planned to install a medium-vacuum tank at BL 4 separated from the storage ring by a MgF window. The terahertz beamline BL 5a [9] covers a range of 0.1 to 7 THz (0.4 to 29 meV) with the limits given by the cut-off frequency of the pipe and the transmittance of a z-cut quartz window. Recent THz results are presented in [10]. For pump-probe experiments, a laser beamline has been commissioned in order to send laser pulses to both, the soft-x-ray and terahertz beamline.

LASER-ELECTRON INTERACTION

In addition to optimizing the temporal, spectral and spatial laser-electron overlap, the shape of the laser waist influences the energy-modulation amplitude. One issue is the electric field of the laser pulse integrated along the modulator axis, another is the optimum modulation of the whole ensemble of transversely distributed electrons. The two criteria are not necessarily fulfilled by the same laser waist size. Control over the laser waist is given by movable focusing elements (lenses or mirrors). An "effective" energy-modulation amplitude (averaged over all electrons) is obtained by scanning the R_{56} value of the chicane and maximizing the CHG intensity, since $R_{56} \cdot \Delta E/E$ is constant for optimum microbunching. First results obtained under variation of the laser waist centered at the modulator are presented in Fig. 3 showing a clear trend with an optimum.

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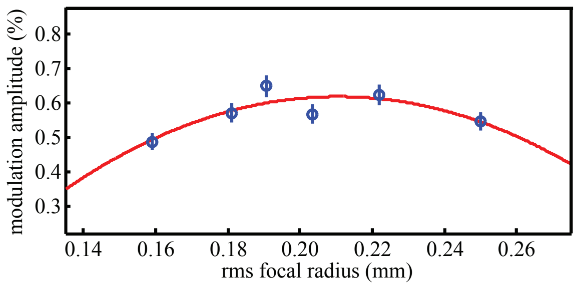

Figure 3: CHG signal as function of the laser waist radius at the center of the modulator showing a parabolic trend.

Motivated by the possibility of creating sharper micro-bunches with tilted wavefronts (see [11, 12] and below), the laser-electron interaction under variation of the crossing angle between the two beams was investigated by moving the electron beam with closed-orbit bumps. While scanning the modulator wavelength, the intensity of coherent THz radiation was recorded at beamline BL 5a using a liquid-helium-cooled InSb bolometer. As shown in Fig. 4, the modulator wavelength for maximum THz signal is blue-shifted by $\Delta\lambda = \lambda_u \theta^2/2$ with increasing crossing angle θ such that the wavelength of undulator radiation in laser direction remains 800 nm.

Optimum laser-electron interaction requires a longitudinally stable electron beam. However, a modulation of the RF phase at twice the synchrotron frequency is routinely used at DELTA in order to improve the beam lifetime and suppress coupled-bunch instabilities. Depending on the amplitude of this modulation, two or three islands rotate in longitudinal phase space at the synchrotron frequency, and the bunch length changes periodically. As reported in [7], the RF phase modulation was synchronized to the laser pulses such that the interaction takes place at the maximum of the electron density (i.e., shortest bunch length and largest energy spread). Depending in detail on the modulation amplitude and frequency, the CHG signal can exceed the value without modulation by up to 30%. Simulations to better understand the dependence of the CHG signal on the longitudinal phase-space distribution are in progress.

CHG RADIATION

The properties of CHG radiation at 400 nm and 200 nm were studied extensively [13] and more details will be given in forthcoming publications. The spectral properties depend critically on the R_{56} value of the chicane and are influenced by longitudinal wavelength variations ("chirp") within the laser pulse. Given by the smaller bandwidth of CHG radiation, the longitudinal coherence was found to be superior to that of spontaneous undulator radiation while the transverse first-order correlation functions measured in double-slit experiments were similar. First investigations in a range from 3 to 18 mA suggest that the coherence properties do not depend on the bunch current.

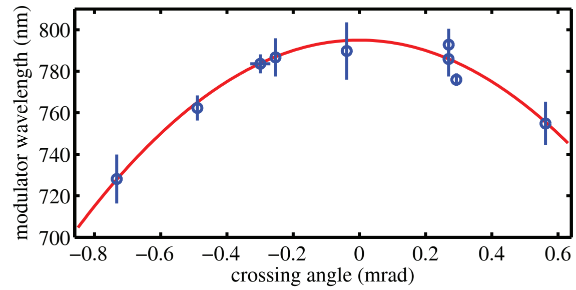

Figure 4: Wavelength of the modulator tuned for maximum THz signal as function of the laser-electron crossing angle.

The angular distribution of CHG radiation was investigated under variation of the laser-electron crossing angle by steering the laser beam. As shown in Fig. 5, the CHG emission angle follows the crossing angle reduced by a factor ≈ 2, which may be an effect of the laser wavefront curvature [12]. The angular offset between background and zero-angle CHG may be due to contributions of incoherent radiation from the modulator and adjacent dipoles.

OUTLOOK: EEHG UPGRADE

In order to generate coherent short-pulse radiation at shorter wavelengths around 10 nm, a transition from the CHG scheme to EEHG is planned [14]. To this end, dipole magnets will be rearranged to increase the length of the U250 straight section from 6.4 m to 20.5 m without changing the storage ring circumference significantly. Two recently delivered electromagnetic 7-period undulators will act as modulators while the present U250 will be used as radiator. Following a 10° dipole magnet, space is provided for an additional undulator in order to perform femtoslicing.

Acknowledgments: The continuous support from our colleagues at DELTA and other institutes, particularly FZJ/Jülich, HZB/Berlin, DESY/Hamburg and KIT/Karlsruhe, is gratefully acknowledged.

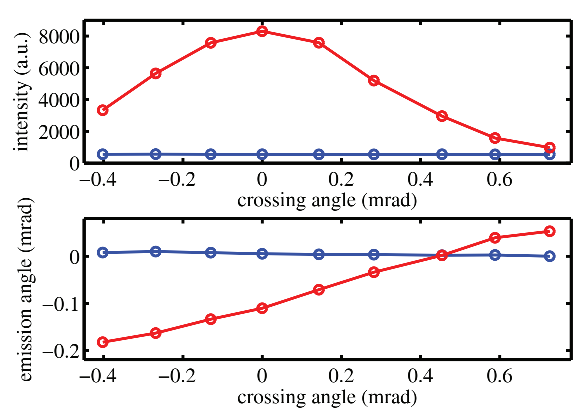

Figure 5: Integrated intensity (top) and mean emission angle (bottom) of CHG radiation (red) and incoherent background (blue) under variation of the laser-electron crossing angle.

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