RECENT RESULTS FROM THE SHORT-PULSE FACILITY 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, a new facility for ultrashort pulses in the VUV and THz regime is currently under commissioning. Here, the interaction of an intense, ultrashort laser pulse co-propagating with the electrons in an optical klystron leads to coherent synchrotron radiation at harmonics of the incident laser wavelength. The aim of the present commissioning steps is to extend the emitted wavelength down to about 50 nm, enabling femtosecond-resolved pump-probe experiments in the VUV regime. Other issues include increasing the photon flux by optimizing the laser-electron interaction and improving the stability and ease of operation of the source.

INTRODUCTION

Extending the applicable wavelengths of ultrashort light pulses down to the VUV and soft x-ray regime is an active field of research. Linac FELs deliver radiation with extraordinary brilliance at photon energies of several keV. The laser-based High Harmonic Generation (HHG) method allows for the generation of ultrashort EUV pulses on a small footprint, serving as a laboratory source. However, HHG is limited in its efficiency and hence in its pulse energy.

Different accelerator-based seeding schemes have been developed using the interaction of intense, ultrashort laser pulses with electrons, enabling conventional synchrotron light sources to reach a new timescale in the sub-ps domain. Among these, the so-called "femto-slicing" is already in routine operation, delivering tuneable radiation for user experiments from the VUV to the x-ray regime [1-3].

A new short-pulse facility employing the Coherent Harmonic Generation (CHG) principle is under commissioning at DELTA [4], a synchrotron light source operated by the TU Dortmund University. Its storage ring has a circumference of 115 m, a nominal energy of 1.5 GeV and a beam current of up to 130 mA in multibunch and 15 mA in single-bunch mode. The project aims at delivering ultrashort synchrotron radiation with pulse durations of the order of 50 fs and a wavelength of 53 nm (23 eV) for photoelectron spectroscopy pump-probe experiments. Additionally, ultrashort THz pulses are generated. CHG was first demonstrated at ACO [5] and later performed at UVSOR II and ELETTRA [6,7].

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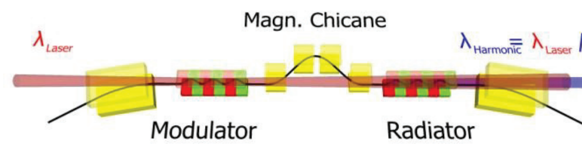

Figure 1: Schematic diagram of an optical klystron, comprising two undulators, separated by a magnetic chicane.

The CHG method is based on the interaction of an intense, ultrashort laser pulse with co-propagating electrons in the first half of an optical klystron (Fig. 1), the so-called "modulator" which is tuned to the laser wavelength. This interaction leads to a sinusoidal modulation of the electron energy with the periodicity of the laser wavelength (Fig. 2). Due to energy-dependent path-length differences in a following magnetic chicane, the energy modulation is converted into a modulation of the electron density.

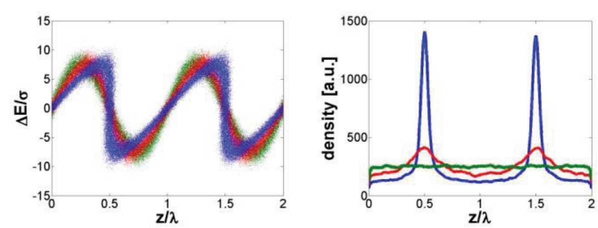

Figure 2: Phase space (left) of energy-modulated electrons and electron density (right) for different R_{56} values of the magnetic chicane.

The shear of the sinusoidal phase-space distribution is proportional to the transfer matrix element R_{56}, introducing higher frequency components into the longitudinal electron density by forming micro-bunches. These lead to coherent emission of synchrotron radiation at harmonics of the laser wavelength in the second part of the optical klystron ("radiator") with a similar pulse duration as the modulating laser pulses. The radiated power scales with the number of electrons squared, decreasing exponentially with increasing harmonic order.

Due to path-length differences in the following lattice, a sub-mm dip is induced in the electron bunch, giving rise to coherent, ultrashort synchrotron radiation pulses in the THz regime [8]. Frequency doubling or tripling the laser pulse prior to entering the modulator allows for the generation of ultrashort pulses at even shorter wavelengths.

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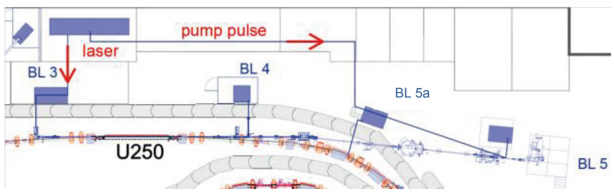

Figure 3: Northern part of the DELTA facility including the laser laboratory, the laser beamline BL3, the diagnostics beamline BL4 and the THz beamline BL5a. A pump-pulse beamline is currently under construction and will send a fraction of each laser pulse to the experimental station at BL5 for pump-probe applications.

SETUP

The short-pulse facility at DELTA is located at the northern part of the accelerator hall (Fig. 3). A commercial Ti:sapphire laser system (Coherent Legend) delivers laser pulses with properties as listed in Tab. 1. Additionally, the laser laboratory is equipped with a SPIDER and a FROG apparatus for laser-pulse length characterization, an optical parametrical amplifier (OPA) for continuous wavelength tuning and a unit for second- (SHG) and third-harmonic generation (THG) of the laser radiation (Tab. 1).

The laser pulses are transported to the undulator via an evacuated beamline (BL 3), comprising a motorized in-vacuum telescope, two motorized mirrors and two transverse diagnostics screens.

The electromagnetic undulator U250, formerly operated as a storage-ring FEL, serves as an optical klystron with independently tuneable modulator, chicane and radiator sections. Via BL 4, the undulator and laser radiation is guided into a diagnostics hutch, where the transverse and longitudinal overlap between laser and electrons is detected and CHG radiation is characterized. Recently, a new setup for the transverse overlap was installed, consisting of two CCD cameras observing the undulator and laser radiation on two screens approximately 7 m apart, without any additional optics in the beam path. Interpreting the so acquired images is easier than the ones obtained by the previous method, in which the radiation source was directly imaged with zoom lenses focused at different distances (Fig. 4).

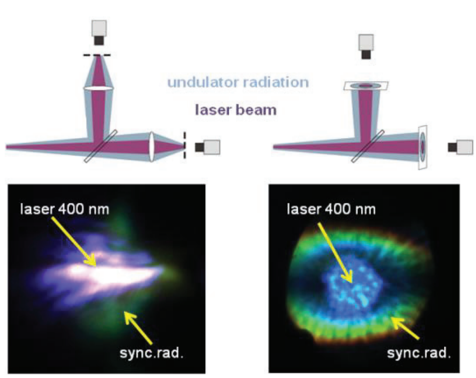

Figure 4: Transverse laser-electron overlap at the undulator (left) and on downstream screens (right). Imaging the radiation source is impaired by optical distortions.

In the future, the beamline BL 5, operated by the Forschungszentrum Jülich, will be used for time-resolved pump-probe measurements.

Table 1: Laser, 2nd and 3rd harmonic pulse energies

	Laser	SHG	THG
wavelength	796 nm	398 nm	265 nm
pulse energy @ 1 kHz	8 mJ	1.8 mJ	0.75 mJ

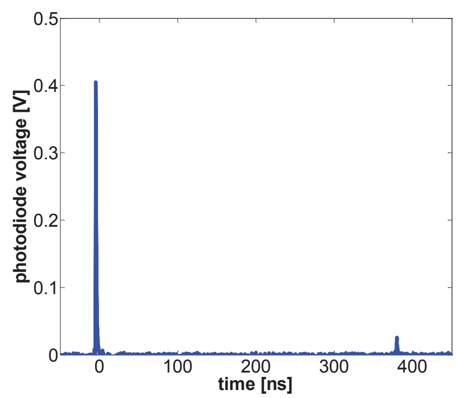

Figure 5: Radiation signals from a single bunch at two subsequent revolutions, with (left) and without (right) coherent contribution.

EXPERIMENTAL RESULTS

The increase in intensity due to coherent radiation is shown in Fig. 5. Here, the radiator was tuned to the 2nd harmonic of the modulating 800 nm laser pulse (with a pulse energy of 3 mJ in this case) and the undulator radiation was detected by a photodiode using bandpass filters to block the laser light. The CHG contribution enhances the radiated power by about a factor of 20, showing good progress compared to the first results [4].

Besides the 2nd, also the 3rd and 4th harmonic of the 800 nm laser pulses were observed, even though the R_{56} value of the magnetic chicane was not sufficient for optimum micro-bunching. Furthermore, the 2nd undulator harmonic of 400 nm CHG radiation was observed. The absorption of UV radiation in air below 200 nm currently prevents the detection of higher harmonics.

By tilting the linear polarization of the laser pulses with a half-wave plate, and thus reducing the projected electric field in the undulator plane, the dependence of the CHG intensity on the laser pulse energy was measured (Fig. 6). Dividing the CHG signal by the bunch current squared corrects for the change of the current during the measurement.

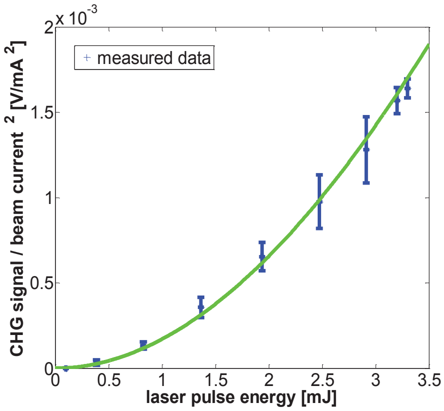

Figure 6: Intensity of the 2nd harmonic of 800 nm modulation wavelength vs. effective pulse energy.

The power of the CHG radiation scales with the square of the bunching factor b_n, a measure of the harmonic content of the density distribution. The bunching factor is proportional to a Bessel's function of the order n of the respective harmonic (e.g. [9]):

$$P_n^{coh.} \propto b_n^2(E) \propto J_n^2(\sqrt{E}),$$

where E is the laser pulse energy. For the measured 2nd harmonic, the data is well described by a Bessel's function of 2nd order squared (Fig. 6).

Beginning of 2012, the modulation wavelength was switched to 400 nm via SHG in order to extend the radiated harmonics to shorter wavelengths.

Two problems arise at this step. Firstly, the pulse energy of 1.8 mJ is smaller than the previously used 3 mJ due to the limited conversion efficiency in the SHG process. Secondly, the material dispersion of telescope lenses, windows and air, leading to a temporal stretching of the modulating pulse, cannot be pre-compensated with the grating compressor of the laser.

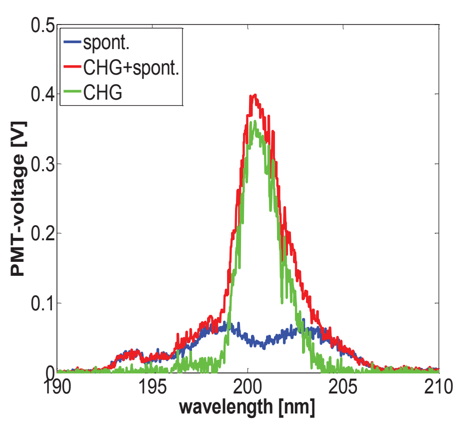

Figure 7: Spectrum of the 2nd harmonic of 400 nm modulation wavelength, showing the spontaneous radiation + CHG (red), spontaneous radiation only (blue) and the difference of both (green).

The spectrum shown in Fig. 7 was obtained with a Czerny-Turner-type spectrometer and a photomultiplier (Fig. 7). With an expected pulse duration of 50 fs, the observed CHG bandwidth (2.4 nm FWHM) yields a time-bandwidth product close to the Fourier limit. The ratio of CHG/spontaneous emission is approximately 8 in this example.

OUTLOOK

In order to increase the coherent signal intensity, the reduction of material dispersion by using a reflective telescope is of great importance. A pre-compensation of the remaining material dispersion via multiple reflections on chirped mirrors is possible, ensuring the minimum pulse duration at the modulator.

Enhancing the stability of the CHG radiation is a major issue. A tight cover for the beam path on the optical table in the laser laboratory is under construction, preventing the beam from being influenced by air turbulence and pressure changes.

For time-resolved photoelectron spectroscopy at BL 5, a wavelength of 53 nm is desired, which is the 5th harmonic of frequency-tripled Ti:sapphire laser pulses. The pulse energy of 0.75 mJ (Tab. 1) limits the achievable energy modulation. On the other hand, energy modulation at smaller wavelength reduces the required value of the matrix element R_{56} for optimum micro-bunching.

In addition, the generation of wavelength-tuneable CHG radiation is planned using the OPA to change the modulation wavelength continuously while tuning the modulator and radiator wavelength at the same time.

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