STATUS OF THE DELTA SHORT-PULSE FACILITY*

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Abstract

Since 2011, a new Coherent Harmonic Generation (CHG) source is under commissioning at the 1.5-GeV storage ring DELTA. Following first experiments using the fundamental wavelength of a Ti:sapphire laser to modulate the electron energy in a small slice of the electron bunches, 400 nm pulses from a second-harmonic conversion unit are used since early 2012. With the radiator tuned to the second harmonic thereof, 200 nm CHG pulses are routinely observed. In order to detect higher harmonics and to proceed to a seed wavelength of 266 nm, an evacuated diagnostics beamline is under construction. Additionally, an existing VUV beamline is being upgraded to allow for the detection of the CHG pulses and their utilization in pump-probe experiments. Furthermore, a dedicated THz beamline provides valuable information about the laser-induced energy modulation of the electrons. In this paper, the status of the project and technical details will be presented.

INTRODUCTION

At free-electron lasers (FELs) based on linear accelerators, good progress is being made in generating ultrashort radiation pulses in the VUV and X-ray regime in order to investigate atomic phenomena on the femtosecond timescale. The large fluctuations of arrival time and spectra of the pulses generated by SASE FELs can be effectively alleviated by seeding the FEL process with external laser pulses, or, most recently, with pulses generated by an upstream undulator [1]. It is nevertheless worthwhile to develop methods to generate ultrashort pulses at conventional synchrotron radiation sources, given the large number of existing facilities and their well-established user communities. One method is Coherent Harmonic Generation (CHG) [2, 3, 4].

The principle of CHG is illustrated in Fig. 1. The interaction between the electrons and a co-propagating laser pulse in a first undulator (the "modulator") causes a periodic energy modulation within a small slice (typically 50 fs long) of the bunch. Tilting the phase-space distribution by means of a dispersive chicane results in microbunches, which radiate coherently at harmonics of the laser wavelength in a second undulator, the "radiator". Typically, the radiator can be tuned to provide ultrashort pulses with reasonable intensity up to the 5th harmonic. Doubling or tripling the frequency of the external laser pulse through nonlinear crystals, as well as the extension of the scheme to so-called Echo-Enabled Harmonic Generation (EEHG) [5], allows for even shorter wavelengths.

At the storage ring DELTA operated by the TU Dortmund University, a new CHG source with focus on user availability is under commissioning since 2011 [6, 7]. The goal is to provide ultrashort pulses at 23 eV (53 nm, the 5th harmonic of 265 nm) for future pump-probe experiments in standard routine operation.

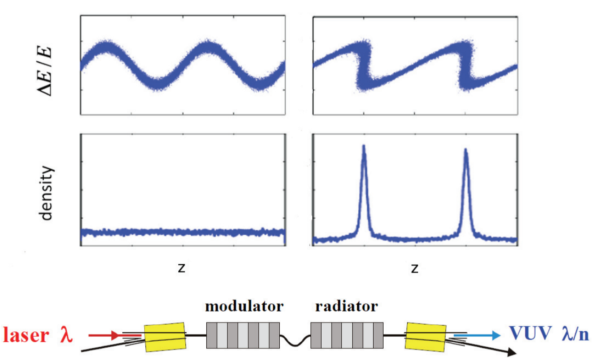

Figure 1: Principle of Coherent Harmonic Generation. In the modulator, a laser pulse imprints an energy modulation onto a short slice of the electron bunch. This slice is micro-bunched in a dispersive chicane, and the micro-bunched electrons then radiate coherently at harmonics of the laser wavelength.

SETUP AND IMPROVEMENTS

DELTA is a 1.5-GeV synchrotron light source with a circumference of 115.2 m (Fig. 2). Located in the northern straight section, the electromagnetic undulator U250 consists of 19 periods of 25 cm each, and was in the past used as optical klystron for storage-ring FEL studies. New power supplies allow separate tuning of the first and last part up to a wavelength of $\lambda = 1$ µm (undulator parameter $K = 12$), while the three central periods serve as a dispersive chicane with magnetic fields up to 0.76 T.

Seed Beamline

A Ti:sapphire laser system (Tab. 1) sends pulses of 35 fs duration through beamline BL3 into the U250 undulator (Fig. 2). The position and size of the laser waist can be changed by remote-controlled mirrors and lenses. A second/third harmonic generation unit (SHG/THG) is located between the laser amplifier and the telescope.

* Work supported by DFG (INST 212/236-1 FUGG), BMBF (05K10PE1, 05K10PEB), and the Federal State NRW

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ISBN 978-3-95450-123-6

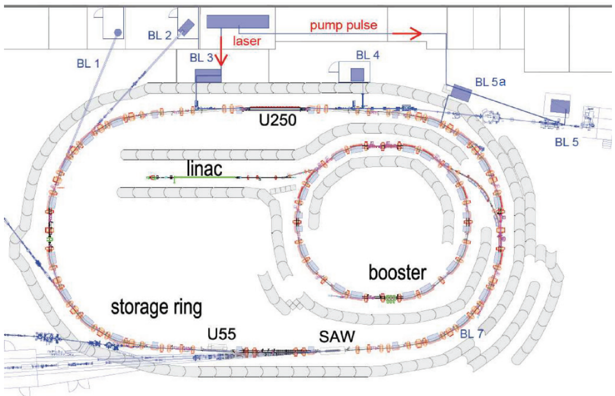

Figure 2: Overview of the DELTA accelerator complex.

Table 1: Laser and 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

Recently, the beamline including the telescope tank has been evacuated and the remaining laser path has been covered. Both measures visibly stabilized the laser spot shape and pointing (Fig. 3), thus increasing the overall stability of the laser-electron overlap.

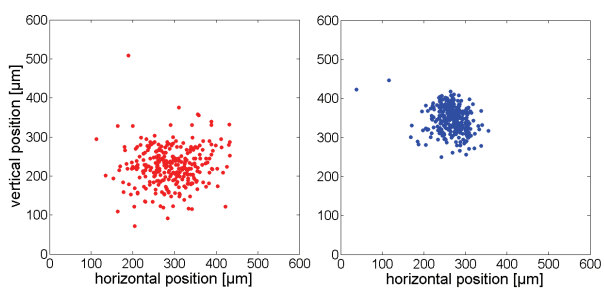

Figure 3: Position of the laser spot at the waist before (left) and after (right) covering the laser path on the optical table.

When working with a seed laser wavelength of 400 nm, however, the present setup yields a severe reduction of the central cone intensity of the laser light in the undulator (Fig. 4), thus limiting the achievable CHG performance. This donut-shaped profile can be attributed partly to the accumulated effects of intensity-dependent index of refraction in two vacuum windows (Fig. 5) and three lenses. Thermal distortions in the first window may also play a role. Furthermore, the accumulated material dispersion after the SHG crystal (at which the laser pulses are shortest) leads to temporal pulse stretching to ∼200 fs in the undulator, thus severely reducing the peak power.

To amend this situation, alterations of several parts of the seed beamline are underway:

- A mirror telescope on the laser table now increases the spot size on the first vacuum window (W1).
- The spot size on the vacuum window between BL3 and the storage ring (W2) is increased by repositioning the window towards the telescope.
- Replacing the 3-lens telescope in the vacuum tank by a reflective telescope will reduce material dispersion.
- Plans exist for repositioning the frequency-up conversion and pulse compression into the vacuum tank.

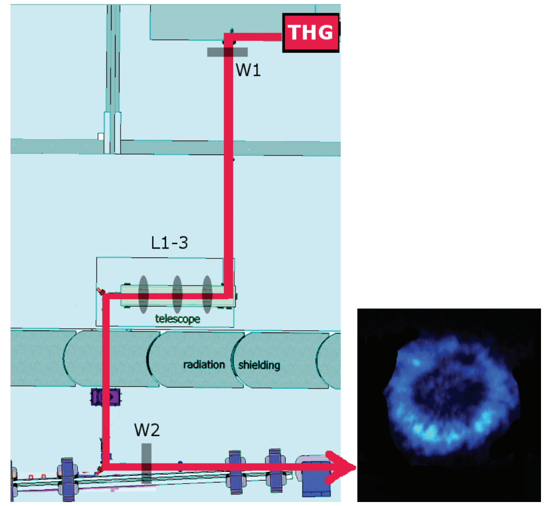

Figure 4: Sketch of the seed beamline BL3 (left). The laser pulses from the THG unit pass through two vacuum windows (W1, W2) and three lenses (L1-3) before entering the undulator, which leads to a donut-shaped laser profile (right).

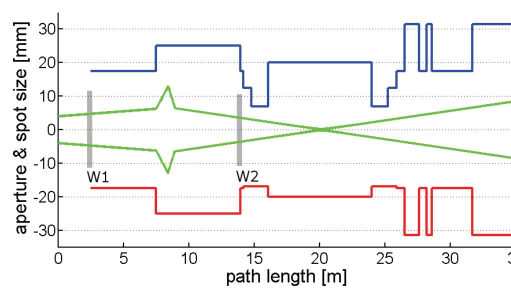

Figure 5: Vertical (blue) and horizontal (red) apertures of the laser path from BL3 to BL4, starting from the THG unit. The green curves denote the spot size (2σ radius) of the laser pulses, which pass through two vacuum windows (W1, W2) before entering the undulator.

Diagnostics Beamline

The undulator radiation can be guided into a diagnostics hutch (BL4) by a water-cooled copper mirror. The temporal overlap of electrons and laser pulses is measured with an accuracy of ∼100 ps using a photodiode that observes the undulator and laser pulses, and to ∼10 ps using a streak camera. Transversely, two different methods have been used to control the overlap between the laser pulses and the undulator radiation (Fig. 6). Firstly, two CCD cameras with different focal lengths look upstream into the undulator. Secondly, the images on two screens, approximately 11 m and 18 m from the modulator, are recorded. While the camera images of the first method are difficult to interpret, the second method suffers from the large opening angles of the beams and the distance from the interaction area. Automating the analysis of the images is planned in order to find and maintain the transverse overlap more easily.

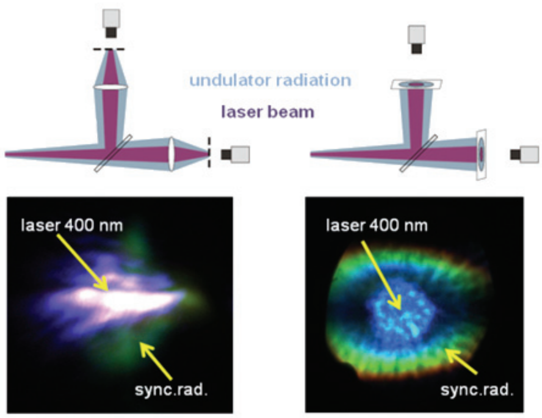

Figure 6: Transverse laser-electron overlap observed in the undulator (left) and on downstream screens (right).

Currently, a new evacuated beamline is being built in order to observe and characterize CHG radiation below 200 nm.

Pump-Pulse Beamline

At the VUV beamline BL5, operated by the Forschungszentrum Jülich, spin- and angle-resolved photoelectron spectroscopy experiments are carried out using the radiation from the U250 undulator. In order to enable pump-probe experiments using the CHG pulses, an evacuated laser beamline has been built to send a fraction of each laser pulse with a variable delay to the experimental station of BL5. Additionally, the pump pulses will be available for experimenters at the THz beamline described in the next paragraph.

THz Beamline

Approximately 13 meters downstream of the undulator, energy-dependent path length differences displace the off-energy electrons of the modulated slice far enough to leave a gap (approx. 100 μm) in the bunch profile. The gap gives rise to coherent THz radiation in a bending magnet. This THz radiation is first deflected by a water-cooled and gold-coated plane copper mirror and then extracted through a dedicated beamline (BL5a), consisting of six toroidal aluminium mirrors, each pair of which forms a Gaussian telescope for wavelength-independent focusing. The THz pulses, detected by a LHe-cooled hot-electron bolometer, provide a sensitive signal for detecting and optimizing the laser-electron overlap in the undulator, but are also used for other purposes. For example, the longitudinal electron bunch profile can be recorded by shifting the timing of the laser trigger with respect to the storage ring RF phase; transverse bunch profiles are studied by transversely displacing the laser pulses using a mirror in the seed beamline [8]. The longitudinal scans revealed that in standard user operation (1.5 GeV electron energy, 25 kW RF power) and for bunch currents up to 15 mA the bunch length stays at a constant value slightly above 100 ps (FWHM). This value is significantly higher than the natural bunch length of 85 ps, which may be attributed to jitter, but current-dependent lengthening due to the microwave instability does not occur at these bunch currents. This is consistent with the absence of spontaneous THz bursts, which have been observed elsewhere [9].

Currently, a Fourier-transform IR spectrometer is under commissioning, which allows to analyze THz pulses within a range of 0.5 - 250 THz.

EXPERIMENTAL RESULTS

CHG signals with an intensity about 20 times higher than that of the spontaneous emission of a single bunch have been achieved [10] with a seed wavelength of 800 nm, showing good progress compared to first results [6]. Furthermore, significant coherent contributions at radiator wavelengths of 265 nm and 200 nm have been recorded, as well as the second harmonic of the radiator tuned to 400 nm. Due to air absorption, higher harmonics could not yet be observed.

The dependence of the CHG intensity on the laser pulse energy E was measured by tilting the polarization vector of the laser pulses with a half-wave plate, thus changing the projected electric field in the undulator plane. For the nth harmonic, the power of the CHG radiation should scale with the squared nth Bessel's function J_n according to $P_n \propto J_n^2(\sqrt{E})$ [11]. The data for the second harmonic confirm this behaviour [10].

Early this year, the seeding wavelength was changed from 800 to 400 nm, and coherent pulses at 200 nm have been routinely observed. A typical spectrum, obtained with a Czerny-Turner spectrometer and a photomultiplier capable of resolving the revolutions of bunches in the storage ring, is shown in Fig. 7. The CHG spectral width of 2.4 nm indicates a time-bandwidth product close to the Fourier limit, assuming a pulse duration of 50 fs.

CHICANE STRENGTH

The dispersive chicane in the current undulator configuration consists of one full and two matching undulator periods with higher magnetic field. This S-shaped chicane yields an R_{56} value that is significantly lower than required for optimum micro-bunching. This has been shown by simulations and by magnetic field measurements, and was recently confirmed by analyzing the spectra of the spontaneous emission of the optical klystron with both undulators tuned to the same wavelength (Fig. 8).

ISBN 978-3-95450-123-6

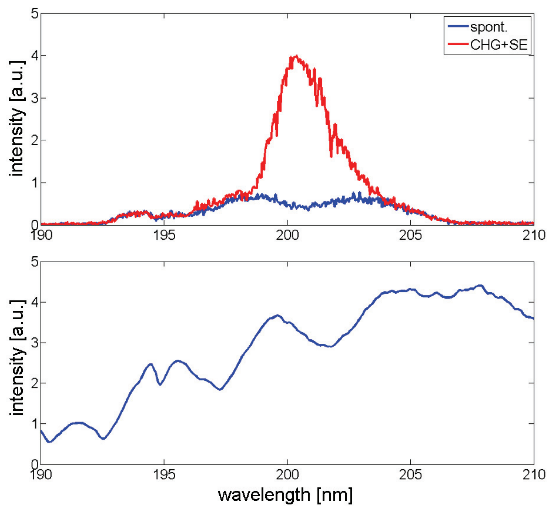

Figure 7: Spectrum of the spontaneous emission (blue) and coherent radiation (red) around 200 nm in air with a laser and modulator wavelength of 400 nm and the radiator tuned to the second harmonic. The top graph was acquired with a scanning PMT spectrometer and additional bandpath filters. The bottom graph shows only the spontaneous emission acquired with a CCD spectrometer without bandpath filters.

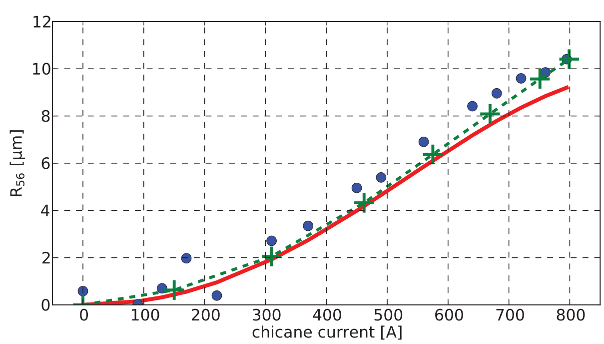

Figure 8: Dispersive strength R_{56} of the U250 chicane, determined by simulation (red curve), by field measurements (green dots), and by measured spectra of the optical klystron with both undulator parts tuned to 200 nm (blue dots).

The chicane provides a maximum R_{56} value of 10 µm, while the modulator with seven periods adds another ∼5.6 µm (for $\lambda = 800$ nm) [12]. According to

$$R_{56} \cdot \frac{\Delta\gamma}{\gamma} \approx \frac{\lambda}{4},$$

for optimum density modulation and an energy modulation of $(\Delta\gamma/\gamma) < 0.5\,\%$, the chicane should be nearly three times stronger ($R_{56} = 34$ µm). At 400 nm and 266 nm, the requirements on the chicane are somewhat relaxed, but on the other hand both the dispersion contribution by the modulator and the available pulse energy are lower (Tab. 1).

A U-shaped chicane would provide a larger R56 value. It is planned to rewire the chicane magnets such that they can easily be switched between the present S-shaped configuration (compatible with the user mode) and a U-shaped chicane.

OUTLOOK

The measures described in this paper will increase both the intensity and the achievable photon energy of the CHG pulses. Reducing material dispersion in the seed beamline is a necessary step in order to maintain a high peak power of the laser pulses in the undulator when seeding with the second or third harmonic of 800 nm. Rewiring the central undulator periods should provide a strong enough dispersive chicane for optimum micro-bunching. An evacuated diagnostics beamline will enable the detection and optimization of the second harmonic of 265 nm, while higher harmonics can be detected by the user beamline BL5. The final goal is to provide ultra-short VUV pulses at 53 nm for time-resolved photoelectron spectroscopy at BL5 in standard routine operation.

As an upgrade to the CHG facility at DELTA, plans for echo-enabled harmonic generation exist [13], which would provide coherent radiation pulses at even higher photon energies. For this purpose an additional undulator is needed, and the northern straight section of the storage ring must be extended.

ACKNOWLEDGEMENT

It is a pleasure to thank our colleagues at DELTA as well as the technical staff of the Faculty of Physics for their continuous support. The project has profited from the expertise of our colleagues at many other labs, in particular DESY, FZJ, HZB, KIT, MLS and SLS. The financial support by the Forschungszentrum Jülich is gratefully acknowledged.

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