ULTRASHORT VUV AND THz PULSE GENERATION AT THE DELTA STORAGE RING *

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Abstract

The optical klystron (two undulators separated by a dispersive section) at DELTA, formerly operated as storage-ring FEL, is seeded with ultrashort pulses from a Ti:Sapphire laser. The thus induced energy modulation of the electron bunch in the first undulator is converted to a density modulation within the dispersive chicane. In the second undulator, the micro-bunched electrons emit ultrashort pulses coherently at harmonics of the fundamental laser wavelength. Additionally, coherent ultrashort THz pulses are generated several meters downstream of the optical klystron by the laser-induced gap in the electron bunch. First results are presented here.

INTRODUCTION

The utilization of sub-ps pulses in the VUV and soft x-ray regime is of great interest in material sciences [1]. Up to now, these are mainly provided by laser-driven High Harmonic Generation sources. Nowadays, SASE FELs generate pulses of extremely high brillance, but due to the limited availability of beamtime at these sources, it is worthwhile to develop methods for short-pulse generation at conventional synchrotron light sources. Apart from reducing the momentum compaction factor, two laser-based techniques have been applied to produce sub-ps pulses.

“Femtoslicing” facilities at BESSY, SLS and ALS are in operation for several years now [2-4]. They make use of a laser-induced energy modulation of the electrons in an undulator. Due to the dispersion in the following dipole magnets, this energy modulation is converted into a transverse displacement of the off-energy electrons. Using an aperture, ultrashort pulses emitted by a subsequent undulator are extracted at high photon energies. The photon rate of this method is very low, because only a very small part of the electron bunch contributes.

Another technique to utilize interaction between an ultrafast laser and electrons in a storage ring is called Coherent Harmonic Generation (CHG). Here, the energy modulation is converted into a density modulation to produce coherent radiation. CHG was first demonstrated at ACO [5], and has been more recently installed at ELETTRA [6] and UVSOR II [7]. At DELTA, a new CHG source is being commissioned and first experimental results have been obtained [8]. DELTA is a synchrotron light source, operated by the TU Dortmund University. Its storage ring has a circumference of 115 m with a maximum beam current of up to 130 mA at a nominal energy of 1.5 GeV.

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CHG CONCEPT

The CHG setup consists of two undulators and a magnetic chicane (Fig. 1), also referred to as “optical klystron”:

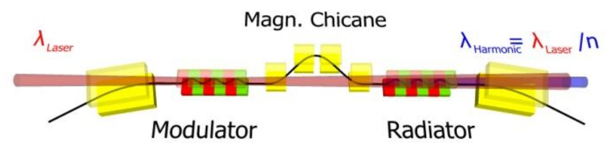

Figure 1: Schematic diagram of the CHG setup.

Inside the first undulator (modulator), the ultrashort laser pulse interacts with the co-propagating electrons, resulting in a sinusoidal energy modulation with a period equal to the laser wavelength. To obtain a maximum modulation amplitude, the undulator has to be tuned to match the laser wavelength

$$\lambda_L = \frac{\lambda_U}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \qquad (1)$$

where λ_L is the wavelength of the laser, λ_U is the undulator period, γ is the Lorentz factor and K is the undulator parameter.

Due to energy-dependent path length differences inside the magnetic chicane, the energy modulation is converted into a density modulation (“micro-bunching”). Depending on the strength of the chicane, given by the transfer matrix element R_{56}, the sinusoidal energy modulation in phase space is sheared, leading to a modulation of the electron density (Fig. 2).

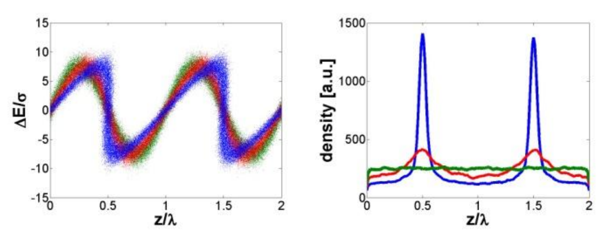

Figure 2: Phase space (left) of energy-modulated electrons and electron density (right) for different R_{56} values.

The periodic structure of the microbunched electrons leads to coherent emission in the radiator. The resulting power depends on the number of electrons squared:

$$P(\omega) = P_1(\omega)\left(N + N^2 b_n^2(\omega)\right) \quad (2)$$

where P_1 is the radiated power of one electron and N is the total number of electrons. The bunching factor b_n is calculated via a Fourier transformation of the normalized electron density. The high harmonic content of the density distribution (Fig. 2) causes the emission of radiation at harmonics of the incident laser light. The radiated power depends on the bunching factor, which decreases exponentially with increasing harmonic order n. A reasonable photon flux is expected up to the 5^{th} harmonic. The duration of the coherent pulses (~50 fs) is determined by the size of the modulated fraction of the electron bunch, which depends on the length of the modulating laser pulse.

Further downstream of the undulator, a gap within the electron bunch is induced, caused by the dispersion of susequent dipole magnets. This leads to coherent emission of THz pulses, also on a sub-ps timescale.

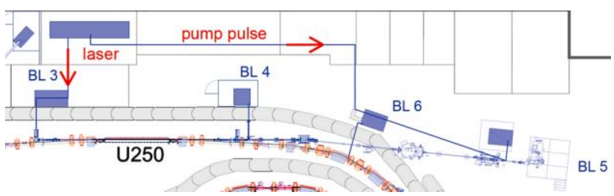

Figure 3: Northern part of the DELTA facility including the laser lab, the laser beamline BL3, the diagnostics beamline BL4 and the THz beamline BL6. An evacuated tube will send a fraction of each laser pulse (pump pulse) to the experimental station at BL5.

SETUP

The setup of the CHG facility at DELTA is displayed in Fig. 3. For energy modulation at a wavelength of 795 nm, a Ti:Sapphire laser is used. It consists of an oscillator and a two-stage amplifier, delivering pulses up to 8 mJ with a duration of approx. 40 fs at a repetition rate of 1 kHz. To enable temporal overlap of the laser pulse and the electron bunch, the laser is synchronized to a subharmonic of the accelerating radio frequency of 499.8 MHz.

Starting from the optical table in the laser lab, an evacuated beamline (BL3) guides the laser pulses into the storage ring. A three-lens telescope focuses the laser beam to the center of the modulator with an adjustable waist position and size. Two remotely controlled mirrors (M1, M2) allow the adjustment of laser position and angle. Two screens (S1, S2) can be moved into the beam for transverse diagnostics (Fig. 4). Optionally, the laser pulses can be reflected back to the optical table after the telescope to observe the shape and longitudinal position of the beam waist, as well as the pulse duration.

The electromagnetic undulator U250 with λ_U = 25 cm serves as an optical klystron. It is configured in such a way that modulator, magnetic chicane and radiator can be

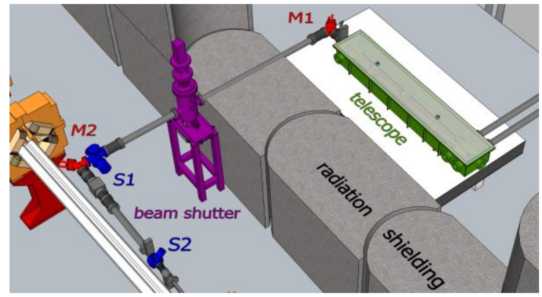

Figure 4: Model of the laser beamline BL3 showing the vacuum chamber with the telescope, beam shutter, mirror chambers M1, M2 and monitor screens S1, S2.

tuned independently. Newly installed power supplies allow for matching the laser wavelength of 795 nm according to Eq. 1 at the full beam energy of 1.5 GeV. A water-cooled mirror is installed at BL4, which can be moved into the radiation path to reflect laser and synchrotron radiation into a diagnostics hutch, where the transverse and longitudinal overlap of laser and electrons is observed [9].

The THz pulses generated downstream of the optical klystron are extracted using BL6 [10]. The THz signal is used as a sensitive diagnostics for the overlap.

BL5, operated by the Forschungszentrum Jülich, presently uses VUV pulses from the U250 for photo-electron spectroscopy and will also be employed for pump-probe experiments.

EXPERIMENTAL RESULTS

First experimental results were obtained during the first week of accelerator operation dedicated to the CHG experiment. Overlap between laser pulses and electron bunches was confirmed by a THz signal at the repetition rate of the laser using a hot electron bolometer and an FFT analyzer.

Shortly afterwards, the first CHG signal was detected using a photodiode and a bandpass filter, only transmitting radiation around 400 nm, corresponding to the second harmonic of the Ti:Sapphire laser (Fig. 5).

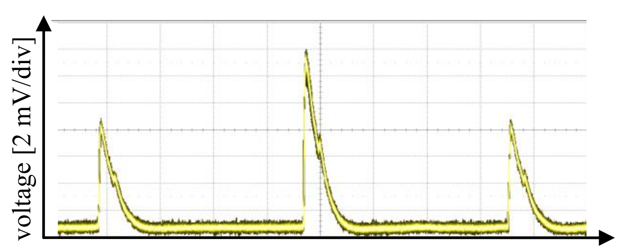

Figure 5: Oscilloscope image of the very first CHG signal at DELTA, showing three revolutions in single bunch mode. The central peak contains coherent contributions, whereas the others arise from spontaneous radiation.

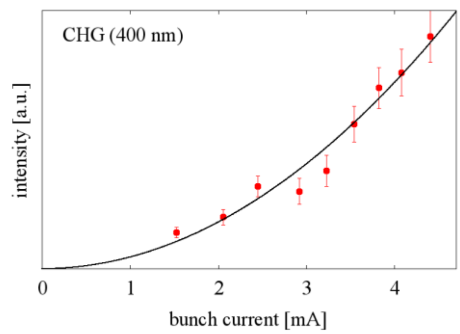

Figure 6: Dependence of the CHG signal (dots) on the bunch current fitted by a quadratic function (line).

At its first observation, the coherent contribution doubled the signal intensity at 400 nm, in later experiments a factor of 6 was achieved. Given that only a tiny fraction (about 1/2000) of the whole electron bunch contributes, the radiation per electron is amplified by more than 10^3 due to coherent emission. Nevertheless, this factor is still low compared to other results, e.g. [6].

Compared to simulations [8], a factor of approx. 2 is missing, presumably due to imperfect laser-electron overlap and optical aberrations. Furthermore, the simulations predict an optimum laser waist size of 400 µm (rms), while the laser waist at the experiments was smaller. Tuning the size of the waist is particularly difficult, since transverse steering of the beam while moving lenses longitudinally cannot be avoided. This may be facilitated once the lenses are motorized and under computer control.

The main reason, however, for not achieving a large coherent enhancement at 400 nm is the limited R_{56} value of the magnetic chicane, which may be increased by rewiring the central coils of the U250 and thus adopting a different chicane scheme. On the other hand, the present R_{56} value will be sufficient once CHG is performed with frequency-doubled or -tripled laser pulses, which is planned for the near future.

Another verification of coherent emission is the power dependence on the electron beam current, as indicated by Eq. 2. As shown in Fig. 6, a quadratic function describes the experimental results well.

The spectrum of the CHG radiation at the second harmonic was measured using a Czerny-Turner-type spectrometer and a photomultiplier (Fig. 7). The spectral bandwidth (FWHM) is found to be 5 nm, indicating a time-bandwidth product close to the Fourier limit.

It is worth mentioning that CHG pulses were produced during user operation, and not only at accelerator shifts. This is important, since the CHG setup is meant to provide ultrashort VUV and THz pulses for pump-probe measurements, without impairing the other experiments.

OUTLOOK

After having collected first data and proven the coherent nature of the generated radiation, the next step is to lower the wavelength of the modulating laser pulses, using non-linear frequency conversion techniques. The mid-term goal is to extract the 5th harmonic of the third laser harmonic, leading to CHG radiation at 53 nm.

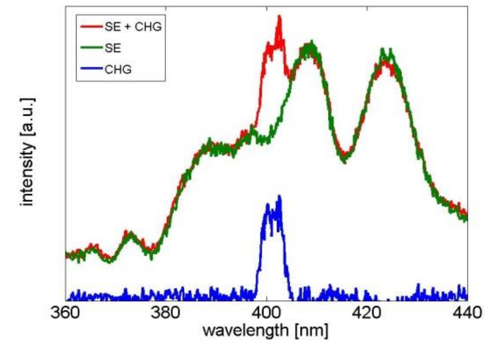

Figure 7: Spectrum of the optical klystron at DELTA with (red) and without (green) laser-induced modulation. The difference (blue) is the spectrum of the ultrashort CHG pulse.

Furthermore, the generation of tunable CHG pulses is planned by modifying the laser wavelength with an OPA and simultaneously adjusting the telescope and undulator parameters.

In order to generate even shorter wavelengths, other methods are currently discussed. One is adding a slicing undulator downstream of the optical klystron, the other is exploiting the echo-enabled harmonic generation scheme [11]. First simulations have indicated their feasibility at DELTA [12].

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