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ECHO-ENABLED HARMONIC GENERATION AT THE DELTA STORAGE RING*

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Abstract

Echo-enabled harmonic generation (EEHG) has been proposed as a seeding method for free-electron lasers but can also be employed to generate ultrashort radiation pulses at electron storage rings. With a twofold laser-electron interaction in two undulators, each followed by a magnetic chicane, an electron density pattern with a high harmonic content is produced, which gives rise to coherent emission of radiation at short wavelengths. The duration of the coherently emitted pulses is given by the laser pulse lengths. Thus, the EEHG pulses can be three orders of magnitude shorter and still more intense than conventional synchrotron radiation. At the 1.5-GeV synchrotron light source DELTA at TU Dortmund University, the worldwide first implementation of EEHG at a storage ring was achieved by reconfiguring an electromagnetic undulator. The paper reviews the experimental setup and describes the present status of the project.

INTRODUCTION

Electron storage rings used as synchrotron radiation (SR) sources are among the primary tools in materials research, physics, chemistry, and biology to study the structure of matter on the atomic scale [1]. However, the typical SR pulse duration is several tens of picoseconds, while phase transitions, chemical reactions as well as electronic or magnetic structural changes take place on the sub-picosecond scale. The femtosecond regime has been accessed by lasers at near-visible wavelengths including high-harmonic generation, and more recently by high-gain free-electron lasers (FELs) in the extreme ultraviolet and X-ray regime [2]. While X-ray FELs serve one user at a time with the repetition rate of a linear accelerator and their number is worldwide still below ten, there are about 50 SR sources supplying multiple beamlines simultaneously with stable and tunable radiation at a rate of up to 500 MHz.

In electron storage rings, pulse durations of 100 fs and below are obtained from a "slice" within a long electron bunch interacting with a femtosecond laser pulse in an undulator (the "modulator") causing a periodic modulation of the electron energy. In a subsequent dipole magnet, off-energy electrons are transversely displaced and their SR from a second undulator (the "radiator") can be extracted using an aperture [3]. This method is employed at BESSY (Berlin, Germany) since 2006 [4]. The ratio of electrons within slice and bunch of $\approx 10^{-3}$ corresponds to the ratio of SR intensity.

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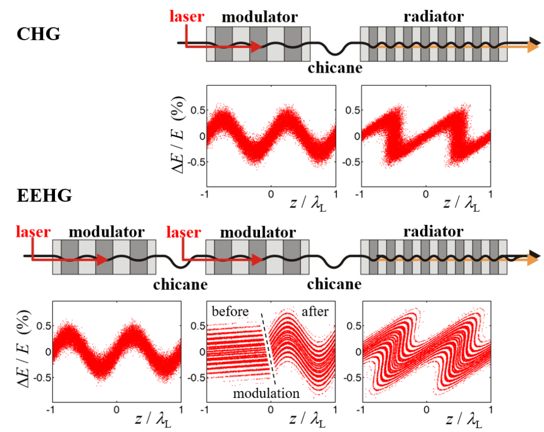

Figure 1: Layout of the CHG and EEHG scheme and respective distributions of electrons in phase space (relative energy offset $\Delta E/E$ versus longitudinal coordinate z in units of the laser wavelength λ_L).

Coherent emission is obtained when the laser-induced energy modulation is converted to a density modulation by a dispersive section ("chicane"). In this case, the SR intensity from the short slice exceeds the incoherently emitted radiation from the whole bunch. In the coherent harmonic generation (CHG, Fig. 1, top) scheme, the radiation power is proportional to b_h^2, the square of the bunching factor at harmonic h of the laser wavelength, which decreases as $b_h \sim \exp(-h^2)$ with increasing harmonic number [5].

In order to reach higher harmonics, echo-enabled harmonic generation (EEHG, Fig. 1, bottom) was proposed as an FEL seeding scheme [6] but can be employed for short-pulse generation at SR sources as well. Here, a twofold energy modulation, each followed by a chicane, leads to a more complex density modulation with the bunching factor decreasing as $b_h \sim h^{-1/3}$. EEHG was demonstrated at linear accelerators [7–10] and was permanently implemented at the FERMI user facility (Trieste, Italy) [11, 12]. It was proposed for SR sources in different ways, placing all undulators and chicanes in one long [13] or two consecutive straight sections [14–16] or even employing the whole storage ring as a chicane [17].

As a worldwide first implementation of EEHG at a storage ring, a demonstration experiment was realized within a length of only 4.75 m [18] at the 1.5-GeV SR source DELTA [19], which is operated by the Center for Synchrotron Radiation of the TU Dortmund University in Germany.

In 2011, the DELTA short-pulse facility based on CHG [13] was implemented using the electromagnetic undula-

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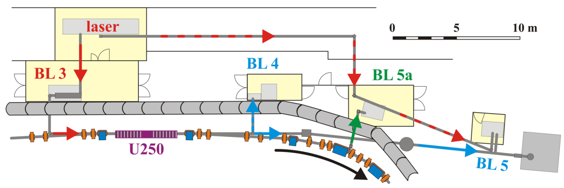

Figure 2: Short-pulse facility at DELTA comprising a laser system, a beamline (BL 3) sending seed pulses to the undulator U250, a diagnostics beamline (BL 4), a soft-X-ray beamline (BL 5), and a THz beamline (BL 5a).

Table 1: Parameters of the EEHG Short-Pulse Facility

Parameter	**Value**
storage ring circumference	115.2 m
electron beam energy	1.5 GeV
max. beam current (3/4 of 192 buckets)	130 mA
max. single-bunch current	20 mA
horizontal emittance	16 nm rad
relative energy spread	$8 \cdot 10^{-4}$
bunch length (FWHM)	80 ps
laser pulse energy (800 nm)	8.0 mJ
pulse energy after SHG (400 nm)	2.6 mJ
pulse energy after SHG (800 nm)	2.7 mJ
laser repetition rate	1 kHz
min. laser pulse duration (FWHM)	40 fs
U250 undulator period	0.25 m
U250 total length	4.75 m
U250 max. K parameter	10.3
periods per EEHG undulator	4
R_{56} of first EEHG chicane	650 µm
R_{56} of second EEHG chicane	80 µm

tor U250 in an optical-klystron configuration (modulator, chicane, radiator) [20]. Figure 2 shows the general layout with a laser beamline (BL 3), a diagnostics beamline (BL 4), a soft-X-ray user beamline (BL 5) for pump-probe applications, and a terahertz beamline (BL 5a). The undulator U250 was rewired in summer 2022 to implement an EEHG configuration (modulator, chicane, modulator, chicane, radiator). Table 1 summarizes the parameters of the storage ring, the laser system, and the new U250 layout.

MAGNETIC LAYOUT

All EEHG undulators and chicanes are part of the electromagnetic undulator U250 comprises 38 pairs of poles. Figure 3 shows the magnetic field in normal undulator mode for users at beamline BL 5 and in EEHG configuration. Boards with copper bars allow to switch between the two magnetic setups within minutes. Split coils at poles 01, 02, 17, 18, 21, 22, 37, and 38 yield 1/4 and 3/4 of the full field by powering one of the partial coils as well as 1/2 or 1/1 field if both coils are excited in opposite or parallel direction, respectively. In the EEHG configuration, endpoles with 1/2 of

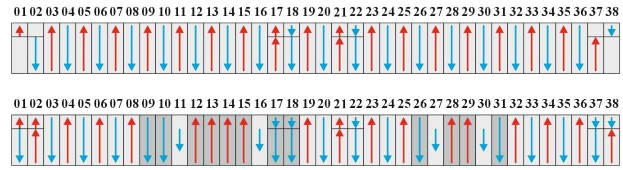

Figure 3: User (top) and EEHG (bottom) configuration of the electromagnetic undulator U250. The arrows indicate the strength and direction of the magnetic field. Gray boxes represent poles contributing to a chicane.

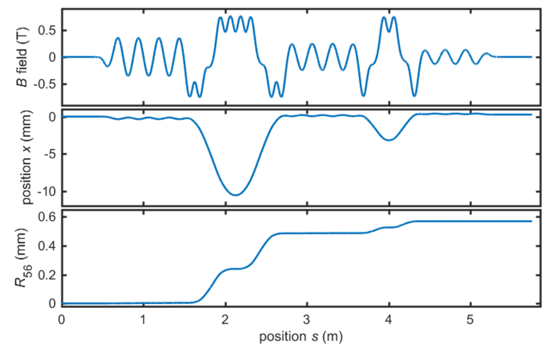

Figure 4: Magnetic field (top), horizontal beam trajectory (center) and integrated R_{56} (bottom) along the undulator U250 in EEHG configuration (undulator wavelengths 800 nm, 400 nm, and 133 nm; chicanes at full current).

the full field are chosen to gain one more undulator period at the expense of a field-dependent beam axis. Instead of installing split coils at poles 11, 16, 27, and 30, the required 1/2 field is obtained by separate power supplies. In total, 14 power supplies are in use to provide a maximum current of 400 A for the undulators and 800 A for the chicanes. This way, all undulators reach a K parameter of 10.3 (wavelength 800 nm at a beam energy of 1.5 GeV) and the longitudinal dispersion R_{56} given in Table 1 is achieved.

Figure 4 shows the magnetic field, horizontal beam trajectory and the integrated longitudinal dispersion in EEHG configuration with the three undulators tuned to 800 nm, 400 nm, and 133 nm, respectively. In this example, different undulator settings before and after a chicane cause a magnetic asymmetry because two undulator endpoles are integrated in the chicane. This, in turn, introduces a nonzero value of the transfer matrix element R_{52} which smears the microbunch structure of electrons with horizontal rms angle $\sigma_{x'}$ longitudinally by $\sigma_z = R_{52} \cdot \sigma_{x'}$. To solve this issue, it turned out to be advantageous that these endpoles are controlled by individual power supplies. Figure 5 shows an example in which the current of pole 27 is reduced and that of pole 30 is increased by the same amount I_{mod} to control the R_{52} value.

SEEDING SCHEME

The two seed pulses required for EEHG are generated from a single Ti:sapphire laser pulse at a wavelength of 800 nm passing a nonlinear crystal (BBO) to generate the

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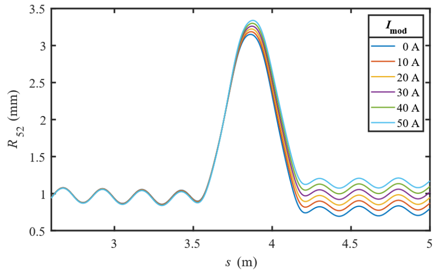

Figure 5: Transfer matrix element R_{52} integrated over position s along the second EEHG modulator and the radiator with an additional current I_{mod} subtracted from pole 27 and added to pole 30. I_{mod} = 34 A minimizes the R_{52} contribution from the chicane between the undulators.

second harmonic at 400 nm as a seed for the second modulator while the residual 800-nm pulse is used to seed the first modulator as shown in Fig. 6. The delay between them is controlled by mirrors on a motorized stage.

The procedure for transverse laser-electron alignment is the following: After coarsely aligning both beams, a coherently emitted THz signal [21] from the 800-nm beam interacting with the electrons in the first modulator is optimized using the in-vacuum mirrors M1 and M2 and their settings are stored. Next, the THz signal caused by the 400-nm beam in the second modulator is optimized using the same mirrors. Finally, the piezo-driven mirrors P1 and P2 are iteratively tuned to recover the previous M1 and M2 settings while maintaining the THz signal.

DIAGNOSTICS

The primary diagnostics for successful laser-electron interaction is coherently emitted THz and sub-THz radiation at beamline BL 5a [21,22]. At beamline BL 4, radiation at and above 200 nm is observed by a Czerny-Turner spectrometer equipped with a gated iCCD camera [23]. For EEHG radiation below 200 nm, an in-vacuum grating spectrometer with a gated microchannel plate (MCP) [24] was commissioned.

A water-cooled in-vacuum mirror (Al coating on a Cu substrate) is suspended from a vertical linear stage to send laser and undulator radiation to beamline BL 4. The horizontal angular control of the mirror was improved using a motorized goniometer [25] to rotate the whole mirror chamber between bellows as shown schematically in Fig. 7.

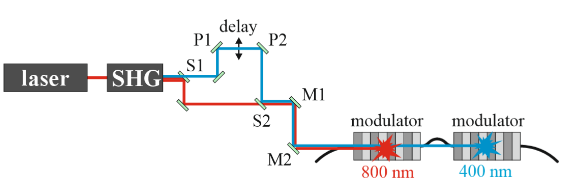

Figure 6: Schematic path of two laser beams after second-harmonic generation (CHG). The beams are split and recombined with single-wavelength mirrors S1 and S2. Position and angle of the 400-nm beam is controlled with piezo-driven mirrors P1 and P2. The multi-wavelength in-vacuum mirrors M1 and M2 act on both beams.

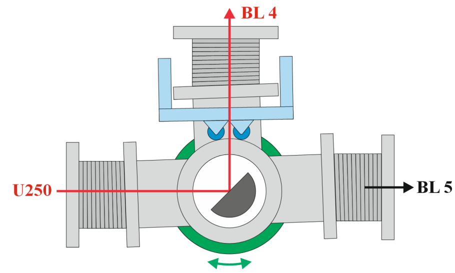

Figure 7: Horizontal angular control of the in-vacuum mirror sending radiation to beamline BL 4. Wheels (blue) take up the force from air pressure pointing in BL 4 direction to reduce the load on the vertical axis of the goniometer (green).

PRESENT STATUS AND OUTLOOK

After successful commissioning with radiation at 267 nm [18], the project was plagued by technical problems, each involving significant investment cost and long delivery times:

- Damage of the MCP.
- Failure of the laser diodes of the Ti:sapphire amplifier.
- High-voltage switch for MCP gating failed.
- Insufficient optical quality of the in-vacuum mirror.

Thus, no new results at shorter wavelengths can be presented at this stage.

It should be emphasized that the whole EEHG setup has a total length of only 4.75 m despite the long period length of the electromagnetic undulator. Figure 8 sketches an optimized setup using permanent magnets for the undulators. Increasing the number of periods would improve the energy modulation and increase the radiation output.

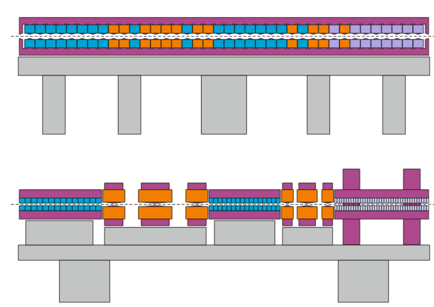

Figure 8: Top: Present EEHG setup with a total length of 4.75 m. Bottom: A possible setup with the same length and permanent-magnet undulators.

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REFERENCES

[1] E. Jaeschke, S. Khan, J. R. Schneider, and J. B. Hastings (Eds.), *Synchrotron Light Sources and Free-Electron Lasers*, Cham: Switzerland: Springer, 2020.

[2] R. Schoenlein *et al.*, "Recent advances in ultrafast X-ray sources", *Phil. Trans. R. Soc.*, vol. A 377, p. 20180384, 2019.

[3] A. A. Zholents and M. S. Zolotorev, "Femtosecond X-ray pulses of synchrotron radiation", *Phys. Rev. Lett.*, vol. 76, p. 912, 1996.

[4] S. Khan *et al.*, "Femtosecond undulator radiation from sliced electron bunches", *Phys. Rev. Lett.*, vol. 97, p. 074801, 2006.

[5] B. Girard *et al.*, "Optical frequency multiplication by an optical klystron", *Phys. Rev. Lett.*, vol. 53, p. 2405, 1984.

[6] G. Stupakov, "Using the beam-echo effect for generation of short-wavelength radiation", *Phys. Rev. Lett.*, vol. 102, p. 074801, 2009.

[7] D. Xiang *et al.*, "Demonstration of the echo-enabled harmonic generation technique for short-wavelength seeded free electron lasers", *Phys. Rev. Lett.*, vol. 105, p. 114801, 2010.

[8] Z. T. Zhao *et al.*, "First lasing of an echo-enabled harmonic generation free-electron laser", *Nat. Photonics*, vol. 6, p. 360, 2012.

[9] E. Hemsing *et al.*, "Echo-enabled harmonics up to the 75th order from precisely tailored electron beams", *Nat. Photonics*, vol. 10, p. 512, 2016.

[10] P. R. Ribič *et al.*, "Coherent soft X-ray pulses from an echo-enabled harmonic generation free-electron laser", *Nat. Photonics*, vol. 13, p. 555, 2019.

[11] C. Spezzani *et al.*, "Echo-enabled harmonic generation at FERMI FEL-1: commissioning and initial user experience", presented at IPAC'24, Nashville, TN, USA, May 2024, paper WEAD3, this conference.

[12] P. R. Ribič *et al.*, "Experimental characterization of the sensitivity of echo-enabled harmonic generation to operating parameters", presented at IPAC'24, Nashville, TN, USA, May 2024, paper MOPG28, this conference.

[13] S. Khan *et al.*, "Coherent Harmonic Generation at DELTA: A New Facility for Ultrashort Pulses in the VUV and THz Regime", *Synch. Rad. News*, vol. 25:5, p. 18, 2011.

[14] C. Evain *et al.*, "Soft x-ray femtosecond coherent undulator radiation in a storage ring", *New J. Phys.*, vol. 14, p. 023003, 2012.

[15] J.-G. Hwang *et al.*, "Generation of intense and coherent sub-femtosecond X-ray pulses in electron storage rings", *Sci. Rep.*, vol. 10, p. 10093, 2020.

[16] X. Yang *et al.*, "Optimization of echo-enabled harmonic generation toward coherent EUV and soft X-ray free-electron laser at NSLS-II", *Sci. Rep.*, vol. 12, p. 9437, 2022.

[17] H. Li, W. Gao, Q. Jia, and L. Wang, "Echo-enabled harmonic generation based on Hefei storage ring", in *Proc. IPAC'13*, Shanghai, China, May 2013, p. 1208, 2013.

[18] S. Khan *et al.*, "SPEED: Worldwide first EEHG implementation at a storage ring", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 1057–1060. `doi:10.18429/JACoW-IPAC2023-MOPM032`

[19] M. Tolan, T. Weis, C. Westphal, and K. Wille, "DELTA: Synchrotron light in Nordrhein-Westfalen", *Synch. Rad. News*, vol. 16:2, p. 9, 2003.

[20] T. Schmidt, "Aufbau des FEL Experiments FELICITA I im sichtbaren und ultravioletten Spektralbereich am Speicherring DELTA", dissertation, University of Dortmund, 1997.

[21] P. Ungelenk *et al.*, "Studies of Ultrashort THz Pulses at DELTA", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 1936–1939. `doi:10.18429/JACoW-IPAC2014-WEPRO002`

[22] C. Mai *et al.*, "Observation of Coherent Pulses in the Sub-THz Range at DELTA", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 823–826. `doi:10.18429/JACoW-IPAC2015-MOPHA023`.

[23] Oxford Instruments, Andor iStar 334T CCD. `https://andor.oxinst.com/products/intensified-camera-series/istar-334t`

[24] HP Spectroscopy easyLight XUV. `https://www.hp-spectroscopy.com/easylight-vuv`

[25] Huber Goniometer 410. `https://www.xhuber.com/de/produkte/1-komponenten/12-rotation/1-kreis-goniometer/410-410a`