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PROGRESS TOWARDS EEHG SEEDING AT THE DELTA STORAGE RING*

B. Büsing†, A. Held, H. Kaiser, S. Khan, C. Mai, A. Radha Krishnan,
Zentrum für Synchrotronstrahlung (DELTA), TU Dortmund, 44227 Dortmund, Germany

Abstract

Seeding of free-electron lasers (FELs) with external laser pulses triggers the microbunching process such that the spectrotemporal properties of coherently emitted FEL radiation are under better control compared to self-amplified spontaneous emission. High-gain harmonic generation (HGHG) based on the interaction of electrons with a single laser pulse is routinely applied at a few FELs, and echo-enabled harmonic generation (EEHG) with a twofold laser-electron interaction has been demonstrated. Both schemes can be adopted in storage rings for the coherent emission of ultrashort radiation pulses. Coherent harmonic generation (CHG) is the counterpart to HGHG without FEL gain. It has been employed at several storage rings and presently provides ultrashort pulses in the vacuum ultraviolet regime at the 1.5-GeV electron storage ring DELTA operated by the TU Dortmund University. EEHG, which allows to reach higher harmonics of the seed wavelength, has not yet been implemented at any storage ring but is pursued at DELTA as an upgrade plan. The paper presents the layout of the envisaged EEHG facility, and it reviews simulation studies and the technical progress towards EEHG seeding at DELTA.

ECHO-ENABLED HARMONIC GENERATION (EEHG)

Based on a twofold laser-electron interaction, the seeding scheme echo-enabled harmonic generation (EEHG) [1] is a promising method to provide ultrashort radiation pulses in the femtosecond regime of wavelengths in the extreme vacuum ultraviolet at storage rings. Co-propagating laser pulses and electron bunches in two undulators (modulators) tuned to the laser wavelength lead to energy modulations, which are converted by dispersive chicanes after the modulators into a complex density modulation, so-called microbunches.

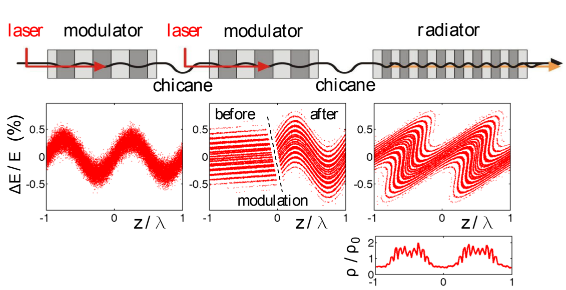

Figure 1: Magnetic setup for EEHG, corresponding longitudinal phase space distributions and the final longitudinal electron density.

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† benedikt.buesing@tu-dortmund.de

Here, the first chicane is strong and forms thin stripes in the longitudinal phase space, while the second weaker chicane generates the microbunches. These michrobunches lead to coherent emission of radiation in the successive radiator tuned to a harmonic of the laser wavelength. The scheme is depicted in Fig. 1.

EEHG AT DELTA

Currently the short-pulse facility at DELTA, a 1.5-GeV storage ring operated by the TU Dortmund University, is based on the coherent harmonic generation scheme (CHG) [2, 3] where only one laser-electron interaction takes place. Modulator, chicane and radiator are realized within a single undulator U250 as shown in Fig. 2 (top). A Ti:sapphire laser system enables seeding with 800 nm laser pulses or their second harmonic.

Storage Ring Optics

To implement EEHG, the short-pulse facility needs to be remodeled to create a long straight section where all components can be arranged directly in one straight section, see Fig. 2 (bottom). The magnet positions were determined by several boundary conditions regarding the beta functions in the modulators to match the laser and electron bunch size, an achromatic straight section to not disturb the longitudinal phase space and to keep the optical functions outside the modified section unchanged as to not influence the other beamlines [4]. To fulfill all the requirements, simulations of the optics of the present and future ring were performed with the simulation code *elegant* [5]. The resulting main parameters of present and future ring are listed in Table 1 and Fig. 3 shows the beta functions of the two setups. Simulations of the dynamic aperture have also been performed [6].

Table 1: Main Parameters of the DELTA Storage Ring

Parameter	Present	EEHG
electron beam energy	1.5 GeV	1.5 GeV
circumference	115.20 m	115.21 m
hor. tune	9.19	8.59
vert. tune	3.28	3.55
mom. comp. factor	$4.9 \cdot 10^{-3}$	$4.7 \cdot 10^{-3}$
rel. energy spread	$7 \cdot 10^{-4}$	$7 \cdot 10^{-4}$
hor. emittance	16 nm rad	22 nm rad
max. hor. beta function	45 m	22 m
max. vert. beta function	51 m	25 m

MAGNETS

The quadrupole magnets as well as the girders and power supplies of the present setup will be reused. The 10° dipoles

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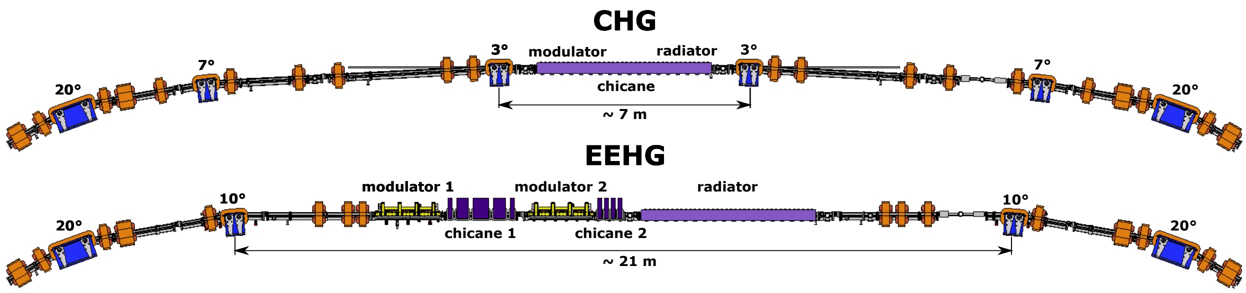

Figure 2: Present (top) northern part of the storage ring with an undulator separated into three parts for CHG and the future modifications to enable a long straight section for EEHG (bottom) with dipoles in blue and quadrupoles in orange.

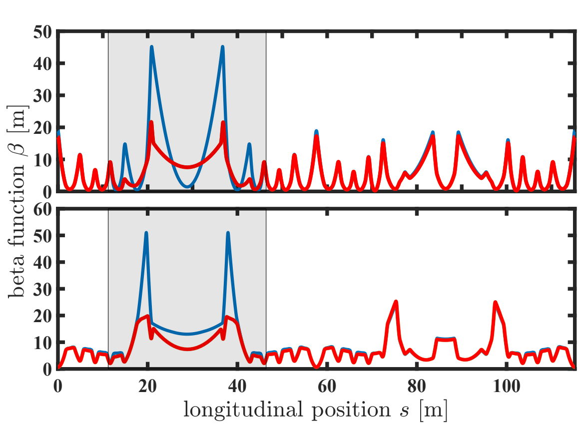

Figure 3: Horizontal (top) and vertical (bottom) beta function β versus longitudinal position s of the present optics (blue) and the future EEHG optics (red). Inside the modified area (gray), the maximum beta function is reduced by more than a factor of two. Outside the EEHG region the beta function does not change significantly.

are generated by powering the coils of the present 7° dipoles with a higher current.

Undulators

The currently used undulator U250 will be reused as radiator in the EEHG setup, and two new shorter undulators U200 with an period length of 200 mm including their girders were procured and will be used as modulators. A test bench to measure the magnetic field properties has been built and one of the new undulators was characterized [7]. The main parameters of the undulators are listed in Table 2.

Table 2: Main Parameters of the New Undulators U200 and the Undulator U250

Parameter	U200	U250
pole gap	40 mm	50 mm
total length	1.85 m	4.85 m
period length	200 mm	250 mm
number of periods	7	17
max. B-Field	0.62 T	0.76 T

Magnetic Chicanes

Simulations of the laser-electron interaction were performed using *elegant* to define the parameters of the chicanes [8]. The strong first chicane will consist of five magnets of three different lengths and alternating polarity to reduce the maximal horizontal deflection, while the weaker second chicane consists of four identical magnets. Simulations of the magnetic field using *CST-Microwave Studio* [9] were carried out to specify the coil properties. The mechanical design of the chicanes is now fixed (see Fig. 4) and the main parameters are listed in Table 3. The design of the girders for the chicane magnets is under development.

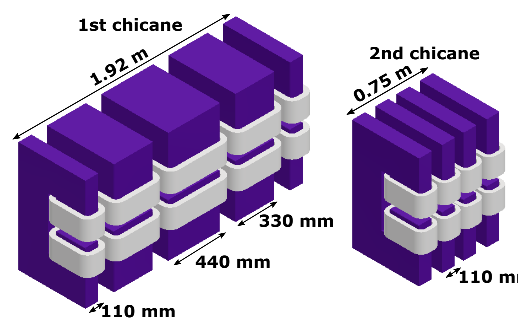

Figure 4: Mechanical design of the strong first chicane (left) and the weaker second chicane (right).

Table 3: Main Parameters of the Designed Chicanes

Parameter	1st Chicane	2nd Chicane
total length	1.92 m	0.75 m
No. of magnets	5	4
max. current	500 A	400 A
max. R_{56}	1.73 mm	0.20 mm
max. hor. deflection	11.15 mm	5.38 mm

VACUUM CHAMBERS

Due to the small gap of the new undulators, new vacuum chambers with reduced height were manufactured for these devices. New chambers to couple in the laser pulse

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and couple out the EEHG radiation in the 10° dipoles were designed taking the laser beam size into account. A preliminary concept for the arrangement of newly manufactured and existing vacuum chambers including necessary bellows, beam position monitors, flanges for external vacuum pumps and built-in pumps, was developed and is shown in Fig. 5. Simulations of the vacuum concept are currently being carried out.

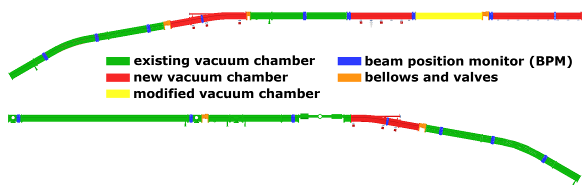

Figure 5: Chamber layout of the envisaged EEHG-based short-pulse facility, reusing existing chambers (green), modified chambers (yellow) and introducing new chambers (red). Beam position monitors (blue) as well as bellows and valves (orange) are considered.

SUCCESSFUL TWOFOLD LASER-ELECTRON INTERACTION

In 2017, a first experiment demonstrated that a twofold laser-electron interaction can be achieved with the current setup. The 400 nm laser pulses generated in a second harmonic generation (SHG) unit and the residual 800 nm laser pulses were focused in the first and last section of the U250, here serving as two modulators with a chicane in between. The delay between the pulses can be controlled optically via a delay stage and fine-tuned by the chicane. The used experimental setup is shown in Fig. 6. The successful twofold energy modulation of the same electrons was verified by measuring the influence on the generated terahertz radiation and on the beam lifetime. Further details can be found in [10].

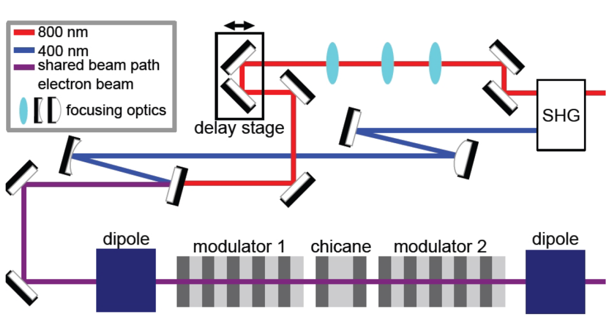

Figure 6: Setup used to achieve a twofold laser-electron interaction. Two laser pulses are focused independently into two modulators.

CONCLUSION

The upgrade of the short-pulse facility of the DELTA storage ring from CHG to EEHG requires a modification of about a quarter of the ring. Several tasks like simulations of the laser-electron interaction and optics, procurement of new undulators and vacuum chambers, and the design of the chicanes, have been completed. A preliminary arrangement of vacuum chambers and a concept of the vacuum system was carried out. A twofold energy modulation of the same electrons within one electron bunch was demonstrated with the current setup. All these points look promising for the first implementation of EEHG at an electron storage ring.

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REFERENCES

[1] G. V. Stupakov, “Beam Echo Effect For Generation Of Short-Wavelength Radiation”, in *Proc. FEL'09*, Liverpool, UK, Aug. 2009, paper MOOB01, pp. 15–22.

[2] R. Coisson and F. De Martini, “Free-electron coherent relativistic scatterer for UV-generation”, *Physics of Quantum Electronics*, vol. 9, p. 939, 1982.

[3] S. Khan *et al.*, “Generation at DELTA: A New Facility for Ultrashort Pulses in the VUV and THz Regime”, *Sync. Radiat. News*, vol. 24, pp. 18–23, 2011.

[4] R. Molo, “Towards Echo-Enabled Harmonic Generation at FLASH1 and DELTA”, Dissertation, TU Dortmund, Germany, 2017.

[5] M. Borland, “elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation”, Advanced Photon Source, IL, USA, LS-287, 2000.

[6] A. Meyer auf der Heide, B. Büsing, S. Khan, D. Krieg, C. Mai, and F. Teutenberg, “The DELTA Short-Pulse Source: Upgrade Plans from CHG to EEHG”, in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 1457–1460. doi:10.18429/JACoW-IPAC2019-TUPGW025

[7] D. Zimmermann, “Aufbau eines Magnetmessstandes zur Feldvermessung von Undulatoren bei DELTA”, master thesis, TU Dortmund University, Germany, 2016.

[8] A. Held *et al.*, “Status of the Short-Pulse Source at DELTA”, in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 1518–1521. doi:10.18429/JACoW-IPAC2021-TUPAB066

[9] CST STUDIO SUITE ®, https://www.cst.com/products/csts2

[10] A. Meyer auf der Heide *et al.*, “Progress Towards an EEHG-Based Short-Pulse Source at DELTA”, in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 2582–2585. doi:10.18429/JACoW-IPAC2017-WEPAB010