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PREPARATORY EXPERIMENTAL INVESTIGATIONS IN VIEW OF EEHG AT THE DELTA STORAGE RING *

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Abstract

At DELTA, a 1.5-GeV electron storage ring operated by the TU Dortmund University, the seeding scheme CHG (coherent harmonic generation), the counterpart to HGHG (high-gain harmonic generation) without FEL gain, is used to provide ultrashort pulses in the femtosecond regime at harmonics of the seedlaser wavelength. To provide higher harmonics and thus shorter wavelengths, it is planned to upgrade the short-pulse facility to the EEHG (echo-enabled harmonic generation) scheme, which has yet not been implement at any storage ring. To install the needed three undulators and two chicanes, about a quarter of the storage ring needs to be modified. The paper presents the layout of the envisaged EEHG facility and the demo project SPEED (Short-Pulse Emission via Echo at DELTA) where all components are realized in a single undulator.

ECHO-ENABLED HARMONIC GENERATION

The seeding scheme echo-enabled harmonic generation (EEHG) [1, 2] makes use of a two-fold laser-induced modulation of the electron energy to generate a complex density modulation. As shown in Fig. 1, the interaction of an ultrashort laser pulse and an electron bunch in an undulator (modulator) tuned to the laser wavelength results in a sinusoidal energy modulation. A strong first chicane after the first modulation leads to thin stripes in the longitudinal phase space due to the energy-dependent path length. With an additional modulator and a second weaker chicane in front of a third undulator (radiator), a periodic density modulation is generated, so-called microbunches. In the radiator, which is tuned to a harmonic of the laser wavelength, these microbunches lead to coherent emission of radiation.

EEHG was proposed and successfully demonstrated as seeding scheme for free-electron lasers (FELs) [3–5] to trigger the microbunching process. Adopted in storage rings, this seeding scheme is a promising candidate to generate ultrashort synchrotron radiation pulses in the extreme ultraviolet regime.

SEEDING AT DELTA

Since 2011, the short-pulse facility at DELTA, a 1.5-GeV electron storage ring operated by the TU Dortmund University, based on the seeding scheme coherent harmonic generation (CHG) [6, 7] provides ultrashort synchrotron radiation pulses. This seeding scheme is based on a single laser-electron interaction and is limited to low harmonics of the laser wavelength. The seeding experiments take place in a single undulator acting as one modulator, one chicane and the radiator. Seeding is performed by 800-nm pulses of a Ti:sapphire laser system or their second harmonic. In addition, radiation in the terahertz regime is coherently emitted in a subsequent dipole magnet. The present setup is depicted in Fig. 2 (top).

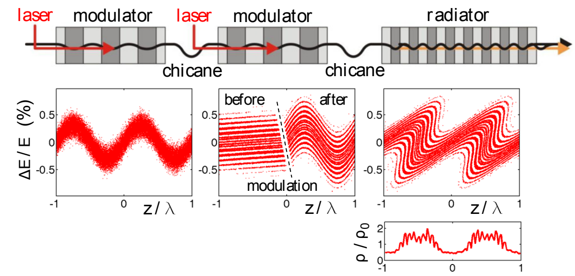

Figure 1: Magnetic setup for EEHG, corresponding longitudinal phase space distributions, and the final longitudinal electron density.

Storage Ring Optics for EEHG

To realize an EEHG-based short-pulse facility at DELTA, it is necessary to remodel a quarter of the storage ring so that all three undulators and the two chicanes can be placed in a single straight section, see Fig. 2 (bottom). The beam optics is optimized using the simulation code *elegant* [8] to fulfill all boundary conditions such as an achromatic straight section to not influence the longitudinal phase space while conserving the optics for the rest of the ring and not changing the source point of the other beamlines [9]. The resulting beta functions are shown in Fig. 3 and the main parameters of the present CHG and the future EEHG optics are listed in Tab. 1.

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

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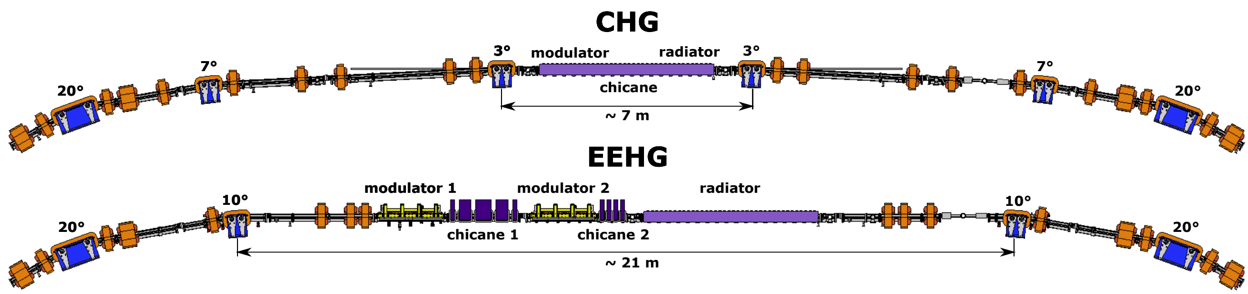

Figure 2: Present (top) northern part of the storage ring with an undulator separated into three parts for CHG and the future modifications to enable a long straight section for EEHG (bottom) with dipoles in blue and quadrupoles in orange.

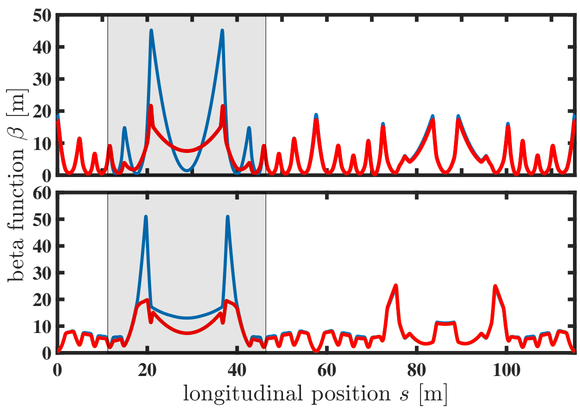

Figure 3: Horizontal (top) and vertical (bottom) beta function versus longitudinal position s of the present (blue) and the future EEHG optics (red). Inside the modified area (gray), the maximum beta function is reduced by more than a factor of two. Outside of the EEHG region, the beta function does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

MAGNETS

In the future magnetic setup, the present quadrupole magnets will be reused while the coils of the 7° dipoles will be powered with a higher current as 10° and one pair of dipoles (3°) will be removed. This allows to generate a straight section of about 21 m with nearly the same ring circumference as before. The future setup is shown in Fig. 2 (bottom).

Undulators

Two new electromagnetic undulators U200 with a period length of 200 mm and their girders are in house and will be used as modulators while the present undulator U250 will act as radiator. The main parameters of the undulators are listed in Tab. 2.

Table 2: Parameters of the Undulators U200 and 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

Dispersive Magnetic Chicanes

The requirements for the magnetic chicanes were obtained by simulation of the laser-electron interaction with *elegant* [10]. Modeling of the magnetic field using *CST Microwave Studio* [11] resulted in five magnets for the first strong chicane and a more conventional four-magnet design for the second chicane, see Fig. 4. The main parameters are listed in Table 3.

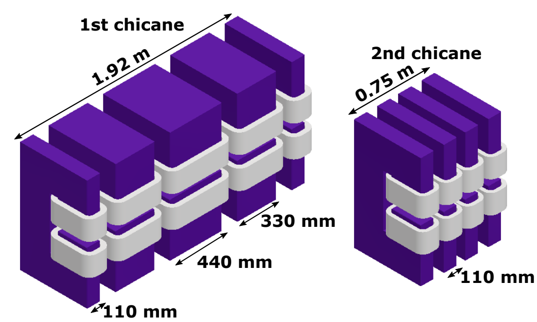

Figure 4: Mechanical design of the strong first chicane (left) and the weaker second chicane (right).

Table 3: Parameters of the 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

For remodeling the short-pulse facility, most of the vacuum chambers will be reused or just slightly modified. For the undulators U200, new vacuum chambers with a reduced

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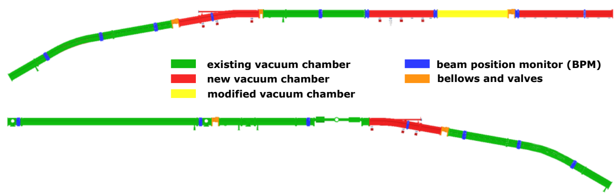

Figure 5: Chamber layout upstream and downstream of the straight section center for the envisaged EEHG-based short-pulse facility, reusing existing chambers (green), modified chambers (yellow) and introducing new chambers (red). Beam position monitors (blue) as well as bellows and valves (orange) are taken into account.

height due to the smaller gap were manufactured, the chamber for the short second chicane is included in one of them. New 10° dipole chambers were designed taking the laser beam size into account. A preliminary arrangement of the chambers including beam position monitors (BPMs), pumping ports for external pumps, bellows and valves was carried out and is shown in Fig. 5.

SPEED: AN EEHG DEMO PROJECT

Before modifying one quarter of the DELTA storage ring, it was decided to realize a fast and less elaborate demonstration experiment to test the feasibily of such a complex seeding scheme for short-pulse generation at a storage ring.

The SPEED project (Short-Pulse Emission with Echo at DELTA) is based on rewiring the present electromagnetic planar undulator U250 to create two sections acting as modulators, two dispersive chicanes, and a radiator. The storage ring remains unchanged and will be operated in single-bunch mode with a typical current of 10 mA. Table 4 summarizes the previous and the new setup and Fig. 6 shows an estimate of the magnetic field as well as the resulting beam position and cumulative R_{56} values as function of the longitudinal position s for both configurations. Note that the usual endpole design of two poles with $1/4$ and $-3/4$ of the magnetic field amplitude, which keeps the electron beam centered to the undulator axis [12], has been abandoned. Instead, a single endpole with $1/2$ of the field amplitude allows to use two more poles while accepting the drawback of a field-dependent horizontal beam shift.

Table 4: U250 in CHG and EEHG Configuration

CHG	modulator	14 poles
	chicane (R_{56})	6 poles (170 μm)
	radiator	14 poles
EEHG	1. modulator	8 poles
	1. chicane (R_{56})	8 poles (471 μm)
	2. modulator	8 poles
	2. chicane (R_{56})	6 poles (72 μm)
	radiator	6 poles

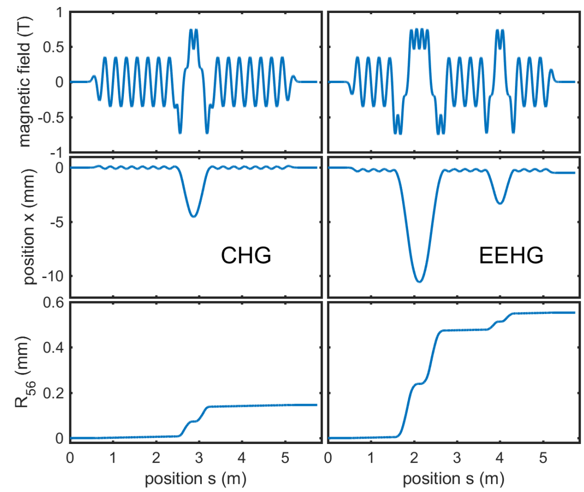

Figure 6: Magnetic field (full current), horizontal beam position, and cumulative R_{56} of the undulator U250 in CHG (left) and EEHG (right) configuration.

The twofold energy modulation is performed using the 400-nm pulses after second-harmonic generation (SHG) of the 800-nm pulses from the present Ti:sapphire laser system plus the residual 800-nm pulses emerging from the SHG process. The temporal overlap between laser pulses and the electron bunches is performed as in CHG operation, i.e., observing laser and spontaneous undulator pulses with a streak camera [13]. The overlap of both laser pulses with the same electrons is established by the methods developed earlier [14, 15]. Due to longitudinal dispersion in the storage ring, each laser pulse causes a dip in the electron density distribution giving rise to coherently emitted THz radiation in a dipole magnet with an intensity given by the interference of radiation from the two dips.

Coherently emitted pulses from the radiator will be detected at and above 200 nm by a Czerny-Turner monochromator combined with an image-intensified gated CCD camera [16]. For smaller wavelengths down to 30 nm, an in-vacuum grating spectrometer will be employed, where a conventional CCD camera images a gated micro-channel plate through a window flange [17].

To our knowledge, the SPEED project at DELTA is the worldwide first implementation of an EEHG scheme at a storage ring. At the time of writing (August 2022), the hardware setup was completed and the correct wiring of all components was checked. Energy modulation with both, 400 and 800-nm pulses, was verified by coherently emitted THz radiation and the spatial as well as temporal overlap was established (see Fig. 7). Values of R_{56} exceeding the conservative estimates in Tab. 4 were found from the interference of radiation from two undulators set to the same wavelength and the chicane between them ("optical klystron") [18]. The next steps in future dedicated beamtime are to perform CHG with the second chicane only, and then set the first chicane to an R_{56} value, which clearly overbunches the first energy modulation, and search for an EEHG signature.

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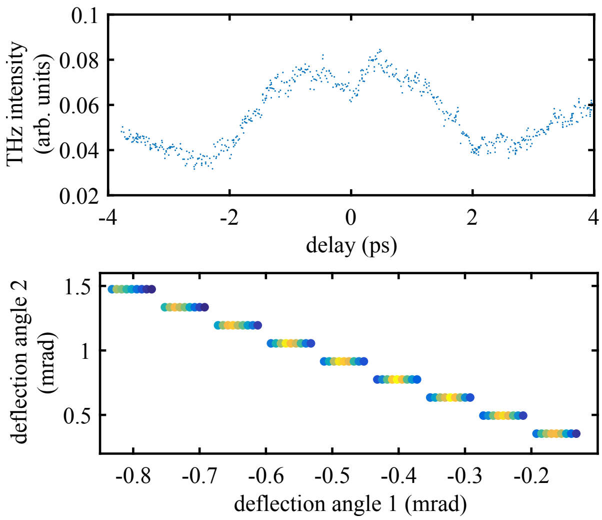

Figure 7: Top: THz signal as function of the delay between two EEHG seed pulses. The dip at zero delay occurs because the number of coherently emitting electrons is reduced when both pulses interact with the same bunch slice. Bottom: Color-coded THz signal as function of deflection angles from the last two laser mirrors optimizing the spatial and angular laser-electron overlap.

In case of success, the project will not only demonstrate EEHG-based short-pulse generation at a storage ring but will prove that this method can be applied within a typical straight section of about 5 m length. Instead of the present undulator with 25 cm period length and only a few magnetic poles for each section, a dedicated setup may be composed of permanent-magnet undulators with tunable gap and period lengths of about 10 cm for both modulators and below 5 cm for the radiator. This way, a compact EEHG device with sufficient intensity for ultrafast-science applications, possibly with all components constructed on a common girder, could be placed in a straight section which is usually occupied by a single undulator.

CONCLUSION

To implement EEHG instead of CHG at the DELTA short-pulse facility, a quarter of the storage ring needs to be remodeled. Towards this upgrade, new optics was developed and most of the necessary hardware like quadrupole and dipole magnets as well as vacuum chambers will be reused or is already procured. Earlier in 2022, it was decided to perform a demo experiment. By rewiring the existing undulator U250, two modulators, two chicanes and a radiator are created in a single device. First tests were performed and we are confident to achieve the first EEHG signal at a storage ring in the near future.

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