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THE DELTA SHORT-PULSE SOURCE: UPGRADE PLANS FROM CHG TO EEHG*

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Abstract

At the synchrotron light source DELTA operated by the TU Dortmund University, coherent harmonic generation (CHG) is employed to provide ultrashort pulses in the vacuum ultraviolet and terahertz (THz) regime. Here, a modulation of the electron energy induced by an interaction of an ultrashort laser pulse with an electron bunch is transformed into a density modulation by a magnetic chicane. This results in coherent emission at harmonics of the laser wavelength as well as THz radiation. With the planned upgrade towards echo-enabled harmonic generation (EEHG), much higher harmonics can be achieved by adding a second laser-electron interaction. The necessary major modifications of the DELTA storage ring and investigations of the laser-electron interaction will be presented.

ECHO-ENABLED HARMONIC GENERATION (EEHG)

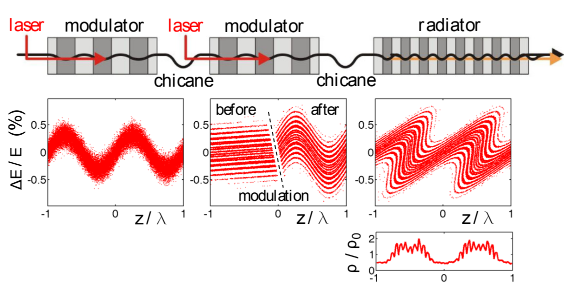

Figure 1: Magnetic setup for EEHG, the corresponding longitudinal phase space distributions and the final longitudinal electron density.

The seeding scheme echo-enabled harmonic generation (EEHG) [1] comprises two laser-electron interactions in undulators (modulators), each followed by a magnetic chicane, as well as another undulator (radiator). As shown in Fig. 1, the first interaction results in a sinusoidal modulation of the electron energy which is transferred into a striated phase space distribution by a strong chicane. The second sinusoidal modulation and chicane tilts the striation which yields a density distribution with a high-frequency modulation. In the following radiator, this distribution results in the coherent emission of higher laser harmonics compared to the coherent harmonic generation (CHG) [2] scheme using a single laser-electron interaction.

While first proposed as a seeding scheme for free-electron lasers, EEHG can also be applied to storage rings to generate coherent sub-ps radiation pulses in the extreme ultraviolet regime.

EEHG AT DELTA

Currently, the short pulse source at the university-based electron storage ring DELTA employs the CHG seeding scheme [6]. Either an 800- or a 400-nm laser pulse interacts with a stored electron bunch in an undulator followed by a magnetic chicane which transforms a sinusoidal energy modulation into a longitudinal density modulation, the so-called microbunching. This gives rise to the coherent emission of laser harmonics with a pulse length corresponding to that of the laser pulse (≈50 fs).

To implement the EEHG scheme at DELTA, the northern part of the storage ring needs to be remodeled to arrange all components in a straight section. The parameters of a new optics are listed in Table 1 together with the parameters of the present optics.

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

Dipole Magnet Configuration

Replacing the present 7- and 3-degree dipoles with 10-degree dipoles enables a long straight section of about 21 m. Two of these dipoles will be reused by increasing the current and, thus, the bending angle. Figure 2 shows a sketch of the northern part of the ring comparing the present and the future positions of magnets and insertion devices.

Quadrupole Magnet Configuration

The present quadrupole magnets can be reused. The quadrupole positions and strengths are optimized by simulations performed with *elegant* [3] to keep the optical functions outside of the EEHG section mostly untouched. Figure 3

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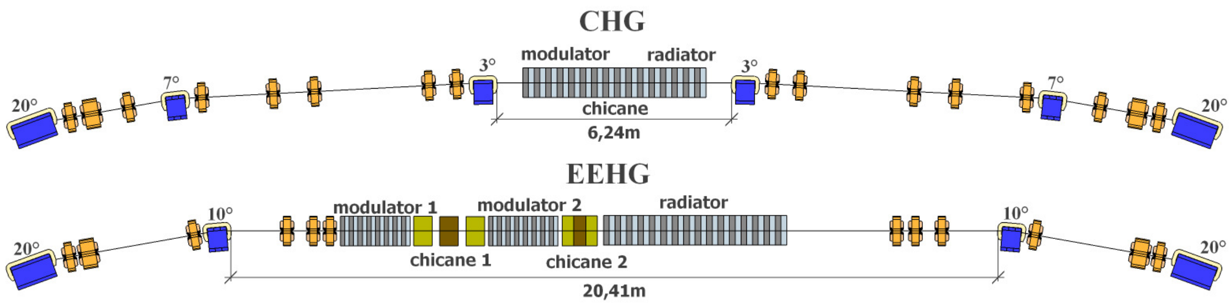

Figure 2: Present (top) northern part of the storage ring with an undulator separated into three parts used for CHG and the future modifications to enable a long straight section for EEHG (bottom) with dipoles in blue and quadrupoles in orange.

shows the beta functions of the present and the future optics with the modified section being highlighted. The beta function in the undulators will in both planes be about 10 m for sufficient laser-electron overlap [4]. Compared to the present optics, the maximum values of the beta functions are reduced by a factor of two. To avoid distortions of the longitudinal phase space structure, the dispersion was reduced to below 1 mm, as shown in Fig. 4.

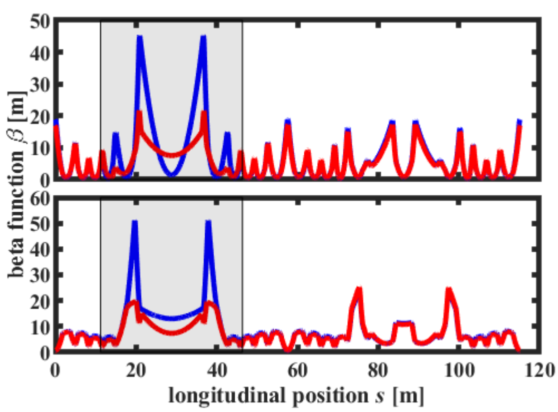

Figure 3: Horizontal (top) and vertical (bottom) beta function β versus longitudinal position s of the present optics (blue) and the future EEHG optics (red). Inside the modified area (gray), the maximum beta function is reduced by more than a factor of two. Elsewhere, the beta function does not change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

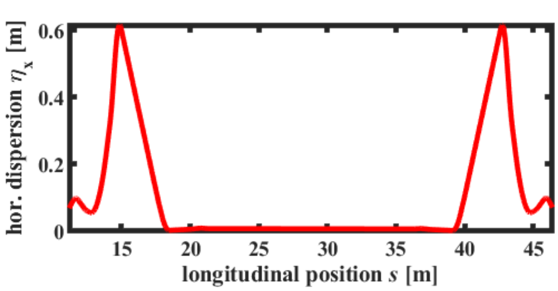

Figure 4: Horizontal dispersion η_x versus longitudinal position s in the EEHG section. The residual dispersion is smaller than 1 mm in the straight section.

Sextupole Magnet Configuration

The strengths of the sextupole magnets in the whole storage ring need to be adjusted in order to compensate the chromaticities and to achieve a large dynamic aperture. Figure 5 shows the dynamic aperture at the place of highest dispersion for particles without momentum offset and with plus or minus 1 % compared to the present on-momentum dynamic aperture. The future optics results in a much larger dynamic aperture in all three cases.

Insertion Devices

The undulator in the present CHG section will be reused as radiator, two new undulators with a period length of 200 mm have been procured and will act as modulators. Furthermore, new vacuum chambers have been designed and ordered. The design of the two dispersive chicanes needs to be finalized.

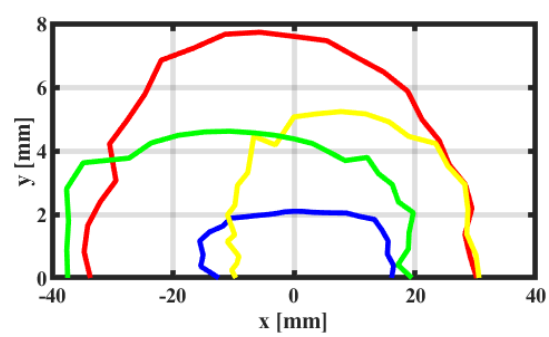

Figure 5: Dynamic aperture for on-momentum particles (red), 1 %- and −1 % momentum offset (yellow, green) for the future optics compared to the present on-momentum dynamic aperture (blue). The off-momentum apertures are centered at the dispersion orbit.

OFF-AXIS SEEDING

Since EEHG requires two individual laser-electron interactions in a straight section of the storage ring, an obvious approach is bringing two laser pulses onto the same axis which requires one pulse to transit a mirror reflecting the other pulse which leads to a degradation of the transiting laser pulse. Another possibility is a crossing angle between

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laser pulse and electron beam. Successful electron energy modulation occurs when the crossing angle equals the emission angle of spontaneous undulator radiation at the laser wavelength and the modulation scales with the spontaneous radiation intensity [5].

Seeding at the Second Undulator Harmonic

With the second harmonic of an undulator only emitting off-axis radiation, an electron energy modulation caused by a laser pulse with a crossing angle and a wavelength matching the second harmonic should be possible. At DELTA, the setup allows to test seeding with a crossing angle and with an undulator tuned to roughly twice the laser wavelength of 400 nm. Laser-induced THz radiation [7, 8], arising from a dip in the longitudinal charge distribution formed after the energy-modulated electrons are longitudinally displaced by dispersive elements downstream of the interaction, enables to monitor the amount of energy modulation.

The spontaneous synchrotron radiation emitted by an undulator has been simulated using the code *SPECTRA* [9]. In the left part of Fig. 6, the angular distribution of the intensity of 400-nm radiation of an undulator tuned to 775 nm is shown. Due to the laser beam divergence of 0.15 mrad, the laser covers a noticeable solid angle which is taken into account by convolving the simulated spontaneous emission with a 2D Gaussian representing the divergence. This results in the expected intensity of THz radiation while seeding with a crossing angle at the second undulator harmonic (Fig. 6, right).

In the experiment, a crossing angle of 0° is obtained by optimizing the laser-electron interaction while the undulator is tuned to the laser wavelength. With the undulator tuned to just below twice the laser wavelength, a crossing angle is introduced by varying the electron beam orbit. The resulting THz signals are shown in Fig. 7. A coarse scan of various crossing angles appear to match the expected distribution (Fig. 7, inset). In a finer scan of the horizontal crossing angle, the simulated spontaneous undulator radiation matches the acquired THz signal when including the laser beam divergence. The small observed asymmetry may result from saturation or nonlinearities of the beam position

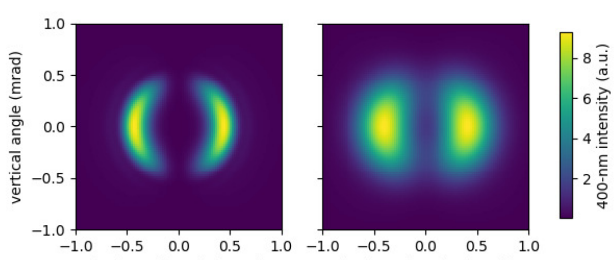

Figure 6: Angular distribution of undulator emission at 400 nm of an undulator tuned to 775 nm (left) as simulated with *SPECTRA* [9]. Convolving the distribution with a 2D Gaussian representing the laser beam divergence results in a realistic distribution of a laser-induced signal (right).

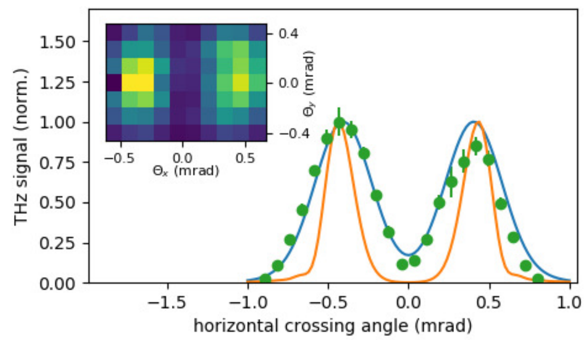

Figure 7: Normalized THz signal (dots) under variation of the horizontal crossing angle at a vertical crossing angle of 0° together with *SPECTRA* simulations without (orange) and including (blue) the laser divergence (see Fig. 6). Inset: THz signal under coarse variation of the horizontal and vertical crossing angles $\theta_{x,y}$ (top left).

monitors (BPM) caused by the large beam offsets of several millimeters required to realize the crossing angles.

It should be noted, that the THz signal indicates the presence of a dip in the longitudinal charge distribution but does not yield information about the suitability of the energy-modulated electron to be transformed into microbunches as shown in Fig. 1. Further investigations, e.g., performing the CHG scheme under this seeding condition to study the microbunching quality, are required.

CONCLUSION

The new optics for the EEHG upgrade of the DELTA short pulse source fulfills the required constraints of a long straight section with small beta functions and practically no dispersion while maintaining the optics outside the modified section and even increasing the dynamic aperture. Major parts of the hardware are already designed and ordered. Successful seeding with a crossing angle has been performed which gives further insight into the laser-electron interaction process may allow for an EEHG seeding setup without the requirement of collinear laser pulses.

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