EEHG AND FEMTOSLICING AT DELTA*

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Abstract

The ultrashort-pulse facility at DELTA, a 1.5-GeV synchrotron light source operated by the TU Dortmund University, is currently based on the coherent harmonic generation (CHG) technique and will be upgraded using echo-enabled harmonic generation (EEHG) in order to reach shorter wavelengths. Laser-induced energy modulation is employed in the CHG and EEHG schemes to create a periodic electron density modulation, but can also be used to generate ultrashort pulses of incoherent radiation at arbitrary wavelengths by transversely displacing the off-energy electrons (femtoslicing). A new storage ring lattice for DELTA will be presented that not only offers enough space for an EEHG and femtoslicing setup, but also allows to operate both radiation sources simultaneously.

INTRODUCTION

DELTA is a 1.5-GeV synchrotron light source operated by the TU Dortmund University. A sketch of the facility is shown in Fig. 1. The storage ring has a circumference of 115.2 m and comprises two undulators (U55, U250) and a superconducting asymmetric wiggler (SAW). The bunch length, approximately 100 ps, determines the duration of the synchrotron radiation pulses. In contrast to that, state-of-the-art femtosecond laser systems generate radiation pulses with durations of about 20-40 fs, but with wavelengths in the near-visible regime. The techniques outlined below allow for the generation of ultrashort synchrotron radiation pulses by a combination of insertion devices and a femtosecond laser system.

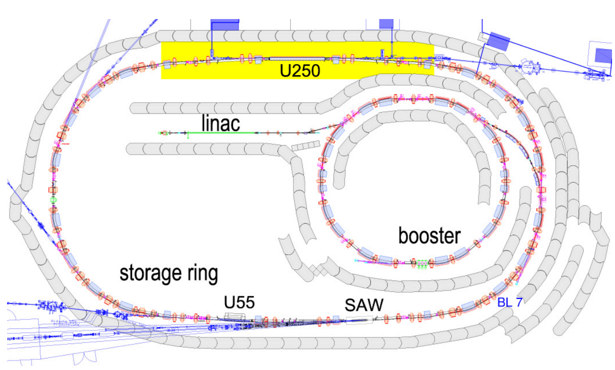

Figure 1: Schematic plan of the DELTA synchrotron radiation facility. The CHG setup is located in the northern part of DELTA denoted by the yellow field.

Coherent Harmonic Generation (CHG)

The CHG scheme [1–3] is shown schematically in Fig. 2. A short laser pulse co-propagates with a long electron bunch in the first undulator, also referred to as modulator. The laser pulse interacts only with a short slice of the electron bunch, resulting in a sinusoidal modulation of the electron energy with the periodicity of the laser wavelength. A subsequent magnetic chicane converts the energy modulation into a density modulation (microbunching) which gives rise to coherent radiation in the second undulator (also called radiator) that is more intense than the incoherent light generated by the whole bunch.

The radiated power of the nth harmonic of the laser wavelength is given by [4]

$$P_n(\lambda) \sim N^2 b_n^2(\lambda), \tag{1}$$

where N is the number of modulated electrons in the bunch, and $b_n(\lambda)$ is the bunching factor [4]

$$b_n(\lambda) \sim e^{-n^2} \tag{2}$$

that decreases exponentially with the square of the harmonic number for CHG. Due to this intrinsic limitation, the CHG technique is limited to harmonics $n < 10$.

The CHG facility at DELTA is under commissioning [5, 6] and located in the northern part of DELTA (see Fig. 1). Presently, the 5th harmonic of 400 nm from frequency-doubled Ti:sapphire laser pulses can be generated. In future, a seeding wavelength of 266 nm will be used in order to produce shorter wavelengths.

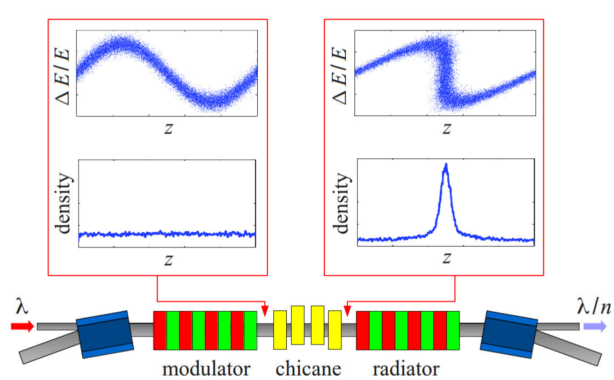

Figure 2: Sketch of the CHG scheme with two undulators and one chicane. The longitudinal phase space plots show the electron distribution before and after the chicane. A peak in the electron density indicates microbunching.

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Echo-Enabled Harmonic Generation (EEHG)

The EEHG scheme [7] is shown in Fig. 3 and utilizes, in contrast to CHG, three undulators and two chicanes in order to generate higher harmonics.

In the first modulator, the electron energy is modulated sinusoidally by a short laser pulse. In contrast to CHG, the first chicane has a large R_{56} value resulting in the pattern shown in the left plot of Fig. 3. A second laser-induced energy modulation and a second magnetic chicane with moderate R_{56} value generates microbunches with a high harmonic content scaling with the harmonic number n as [8]

$$b_n(\lambda) \sim n^{-\frac{1}{3}}. \tag{3}$$

The EEHG technique was successfully tested at FELs at SLAC [9] and SINAP [10] and is planned for FLASH [11]. Studies exist how to apply EEHG at storage rings [12–14], and a possible layout for DELTA will be presented in this paper.

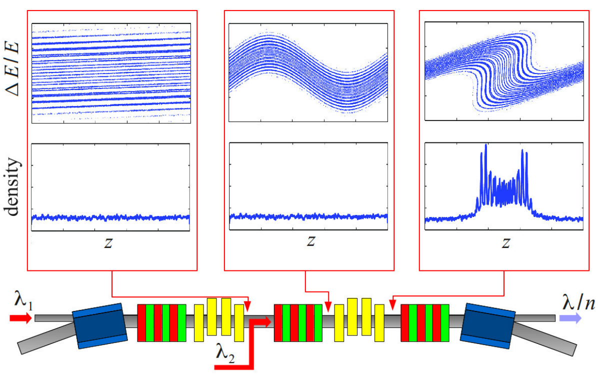

Figure 3: Sketch of the EEHG scheme with three undulators and two chicanes. The longitudinal phase space plots show the electron distribution after the first chicane, after the second undulator and after the second chicane.

Femtoslicing

In the CHG and EEHG scheme, the coherent radiation has to be more intense than the incoherent light from the whole bunch since there is no geometrical separation of coherent and incoherent radiation. Another way to generate ultrashort synchrotron radiation pulses is known as femtoslicing [15]. Here, the modulator in which a laser-induced energy modulation takes place is followed by dispersive magnetic elements leading to a geometric separation of the off-energy electrons. Ultrashort incoherent synchrotron radiation with arbitrary wavelength can be extracted from these electrons by an aperture. Femtoslicing was demonstrated and routinely used at ALS [16], BESSY [17] and SLS [18].

OPTICS REQUIREMENTS FOR EEHG

Since the EEHG scheme employs three undulators and two chicanes, the most important requirement is to retain the microbunching until the electrons reach the radiator. Since the R_{51} and R_{52} matrix elements of dipole magnets would cause additional longitudinal displacement, all EEHG elements should be placed in the same straight section. The typical length of such a setup is about 10 m.

In a drift space, the longitudinal displacement between the nominal particle with $x'_0 = 0$ and a particle with a horizontal angular deviation x' is approximately given by

$$dL = \frac{1}{2}\left(x'\right)^2 ds, \tag{4}$$

where s is the position along the drift space. Considering the electron distribution at a beam waist within the drift space, the rms angular deviation is given by

$$x'_{\rm rms} = \sqrt{\epsilon_x/\beta_0}, \tag{5}$$

where ϵ_x is the horizontal emittance and β_0 is the horizontal beta function at the waist. The longitudinal displacement for a drift space of the length L and $x' = x'_{\rm rms}$ reads

$$\Delta L = \int_{-L/2}^{L/2} \frac{\epsilon_x}{2\beta_0} ds = \frac{1}{2}\epsilon_x \frac{L}{\beta_0}. \tag{6}$$

This shows that the beta function should be large and that the horizontal emittance of the storage ring will be a limiting factor for schemes like EEHG at storages rings (the effect caused by the vertical emittance is assumed to be negligible). The longitudinal displacement ΔL should be of the order of $\lambda_r/10$ or smaller, where λ_r is the desired wavelength.

NEW OPTICS FOR DELTA

The CHG setup is located in the northern part of DELTA (see Fig. 1). The undulator U250 is placed in a straight section between two 3- and 7- degree dipole magnets as shown in Fig. 4. Additional undulators and chicanes for EEHG and femtoslicing cannot be installed since the free space is limited. Furthermore, the optics has to fulfill the above-mentioned requirements. One solution for EEHG at DELTA is explained in [13] where the key point is to increase the straight section by exchanging the 3- and 7-degree dipole magnets. However, this configuration provides no space for a femtoslicing undulator. Another solution allows to install both EEHG and femtoslicing at DELTA. The simulations were performed using the code *elegant* [19].

Correction for Strong Wiggler Fields

The vertical focusing effect of the superconducting wiggler (SAW) disturbs the vertical beta function significantly. Two matching quadrupoles before and after the SAW can be used to correct the distortion. The present vertical beta function with the SAW turned off and on is shown in Fig. 6. With SAW on, the maximum vertical beta function is nearly 100 m. The new optics with SAW on generates a similar vertical beta function as the present optics with SAW off.

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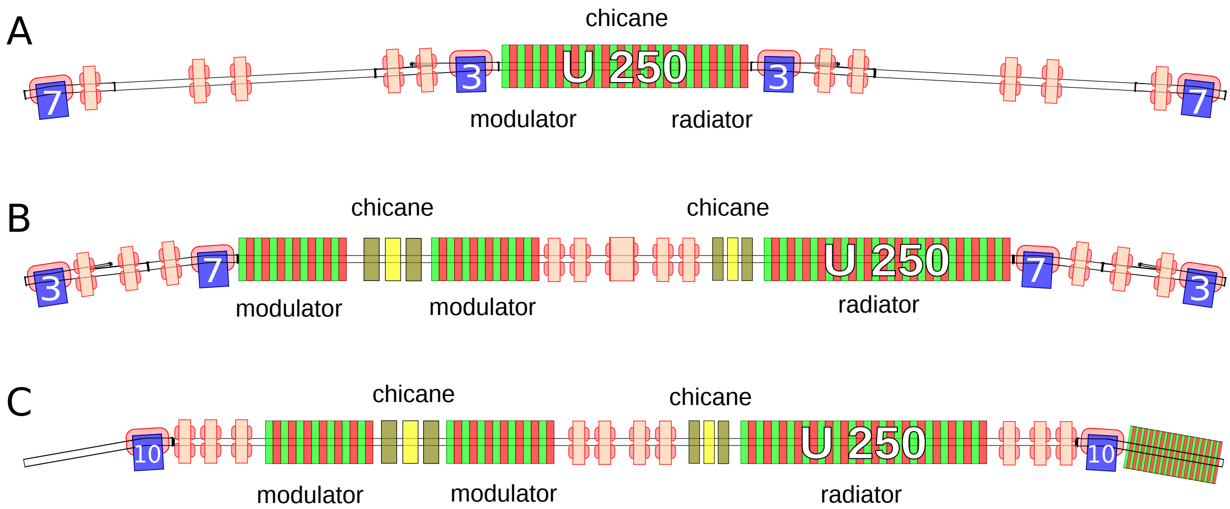

Figure 4: Schematic view of the present CHG setup (A) at DELTA and a possible EEHG configuration, increasing the length of the straight section by changing the bending angle of the adjacent dipole magnets from three to seven degrees (B). If this angle is increased to 10 degrees (C), one pair of dipole magnets is obsolete and space for another undulator, which may be employed as a femtoslicing radiator, is available.

Figure 5: The present vertical beta function with SAW off (blue) and SAW on (black) versus longitudinal position s. The vertical beta function of the new optics with correcting quadrupoles (red) with SAW on agrees well with the present one with SAW off.

New Dipole Configuration

Additional space can be generated by replacing the 3- and 7-degree dipole magnets by 10-degree magnets as shown in Fig. 4, in fact, the present 7-degree magnets can be reused with higher coil current. The straight section between the 10-degree dipole magnets will have a length of about 20 m and offers enough space for the EEHG setup. Additionally, about 2.50 m after the dipole magnet are available for a femtoslicing undulator. In this configuration, the circumference of the storage ring is not changed, but the straight section is transversely displaced by 5 cm.

Figure 6: The present (blue) and new (red) horizontal beta function versus longitudinal position s. The center of the undulator is located at 30 m.

New Quadrupole Configuration

In the new configuration, the horizontal beta function does not exceed 25 m and the vertical beta function does not rise beyond 40 m. Both beta functions agree well with the present ones outside the northern part of the ring. The horizontal dispersion function of the present and new configuration is shown in Fig. 8.

Femtoslicing Simulation

Following the laser-induced energy modulation, the electrons were tracked up to the entrance of the femtoslicing undulator using *elegant* [19]. The angular distribution of the radiation generated by an on-axis electron in the undulator was simulated with the code *spectra* [20] and folded

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with the electron angular distribution. The result is shown in Fig. 9 demonstrating an excellent angular separation of the short-pulse radiation with the new optics setup.

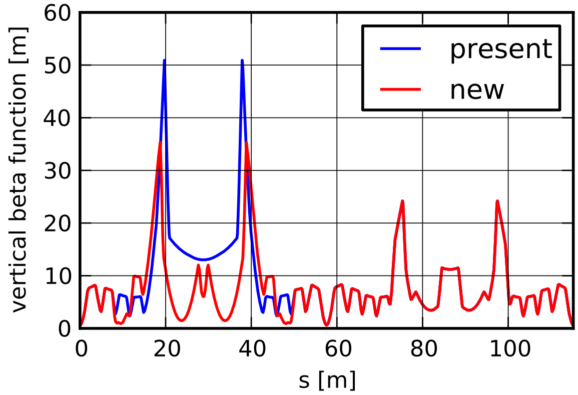

Figure 7: The present (blue) and new (red) vertical beta function versus longitudinal position s.

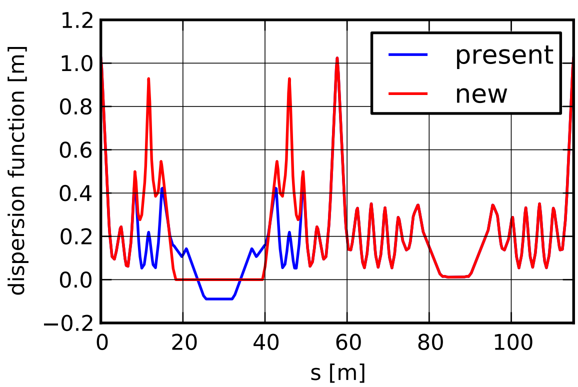

Figure 8: The present (blue) and new (red) horizontal dispersion function versus longitudinal position s.

CONCLUSION

The aim of the planned EEHG project at DELTA is to generate ultrashort synchrotron radiation pulses with wavelengths in the 10 nm regime. The optics presented in this paper allow to install EEHG and femtoslicing at DELTA. However, further optimization with respect to the effect described by Eq. 6 is required. Furthermore, the increase of the horizontal dispersion of the storage ring, as shown in Fig. 8, would increase the horizontal emittance and should be reduced.

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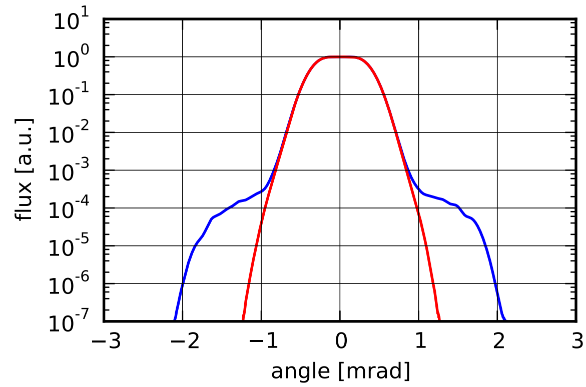

Figure 9: The angular distribution of radiation at 708 eV generated by the femtoslicing undulator for electrons without energy modulation (red) and with energy modulation (blue).

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