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A NEW METHOD TO GENERATE ULTRASHORT AND COHERENT PULSES OF SHORT-WAVELENGTH SYNCHROTRON RADIATION*

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Abstract

A laser-based method to generate ultrashort pulses of synchrotron radiation in electron storage rings is coherent harmonic generation (CHG) using two undulators to produce coherent radiation at harmonics of the initial laser wavelength by microbunching. The bunching factor and thus the pulse intensity, however, decreases exponentially with increasing harmonic order. Echo-enabled harmonic generation (EEHG), proposed in 2009 as FEL seeding scheme, can be used to produce short synchrotron radiation pulses at higher harmonics, but requires three undulators in a straight section. In this paper, a less space-consuming method based on seeding with intensity-modulated laser pulses is introduced, which also has the potential of significant bunching factors at high harmonics.

INTRODUCTION

The advent of linac-based free-electron lasers (FELs) with extremely intense and ultrashort pulses in the femtosecond range has opened up new opportunities for time-resolved studies of ultrafast atomic phenomena. However, only four FELs with sub-visible wavelengths have yet been commissioned and they are essentially single-user facilities with 5-120 bunches (or bunch trains) per second [1–4]. On the other hand, synchrotron light sources based on electron storage rings serve many users simultaneously with a typical bunch rate of 500 MHz and very stable beams, but the pulse duration is 30-100 ps (FWHM). With more than 50 synchrotron light sources in operation worldwide [5], it is worthwhile to investigate methods to extend their capabilities towards shorter pulse duration and higher peak intensity.

In an electron storage ring, the synchrotron motion translates a natural energy spread of typically $\sigma_E \approx 10^{-3}E$ (rms) into a bunch length, depending on the radiofrequency (RF) voltage and momentum compaction factor $\alpha \approx (\Delta L/L)/(\Delta E/E)$. A strong reduction of α at the expense of bunch charge and beam emittance is used at several synchrotron light sources to shorten the bunches to a few picoseconds, see e.g. [6].

SHORT-PULSE GENERATION

Rather than shortening the bunches further, the femtosecond regime is more easily accessible by extracting synchrotron light from a short fraction, a "slice", of the bunch. A femtosecond laser pulse co-propagating with an electron bunch through an undulator (the "modulator") tuned to the

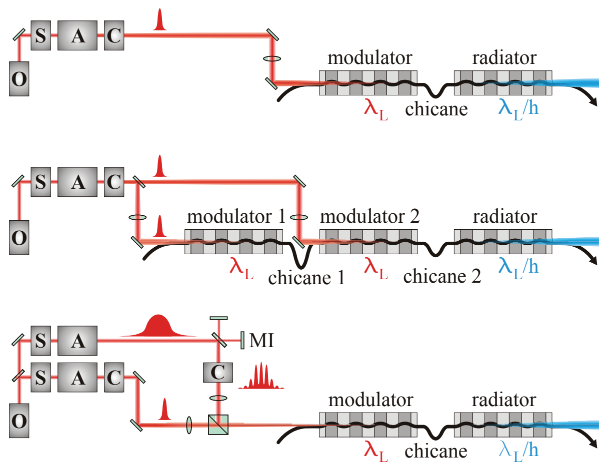

Figure 1: Top: Coherent harmonic generation (CHG) using a laser-induced electron energy modulation in an undulator ('modulator'), converted to a density modulation in a chicane and coherent radiation in a second undulator ('radiator'). Center: Echo-enabled harmonic generation (EEHG) based on laser-electron interaction in two modulators. Bottom: New method with laser-electron interaction at different times in the same modulator. Also shown: laser oscillator (O), stretcher (S), amplifier (A), compressor (C), and Michelson interferometer (MI).

laser wavelength causes a sinusoidal modulation of the electron energy within the bunch slice. Femtosecond laser pulses are typically generated by Ti:sapphire lasers at a wavelength of 800 nm (photon energy $E_P = 1.55$ eV). With a pulse energy E_L in the mJ range ($\approx 10^{16}$ eV) and a pulse duration around $\sigma_L \approx 20$ fs (rms), the modulation amplitude [7]

$$\Delta E \approx 0.2\,\sqrt{E_L E_P}\,\sqrt{M_U/M_L} \qquad (1)$$

will exceed the natural energy spread of the electron beam. The expression is valid as long as the number of undulator periods M_U is smaller than the number of optical cycles $M_L = 2\sqrt{2\ln 2}\,c\,\sigma_L/\lambda_L$ per FWHM pulse length.

One way to exploit the energy modulation in a second undulator (the "radiator") is to transversely displace the off-energy electrons in dipole magnets, providing a spatial separation between the short radiation component from the slice and the long component from the rest of the bunch [8–11]. Another method making use of the laser-induced energy modulation is known as coherent harmonic generation (CHG) [12–15], see Fig. 1 (top). Here, a density modulation (microbunching) is created by energy-dependent path length differences in a magnetic chicane, allowing to generate coherent radiation at harmonics of λ_L in the radiator. The

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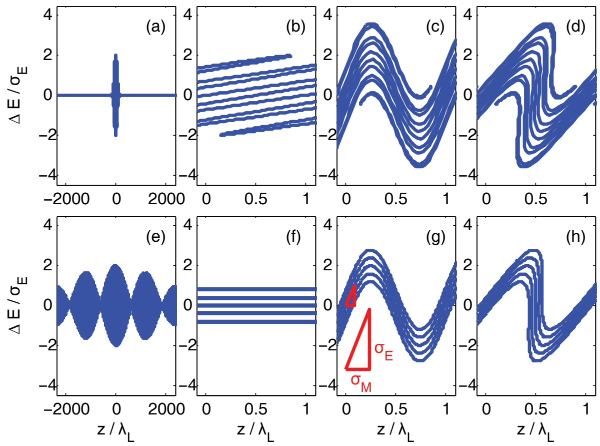

Figure 2: Schematic phase space diagrams, i.e., relative energy offset versus longitudinal coordinate in units of the seed wavelength for EEHG after (a) modulator 1, (b) chicane 1, (c) modulator 2, (d) chicane 2, and for DECHG showing the effect of (e) first modulation, (f) 1/4 synchrotron period, (g) second modulation, and (h) chicane. Note the different scales. The red triangle in (g) refers to Eq. 3.

radiation power at the hth harmonic is

$$P = P_{\mathrm{long}} + P_{\mathrm{short}} = P_e \left\{ n_{\mathrm{long}} + b_h^2 n_{\mathrm{short}}^2 \right\}, \qquad (2)$$

where P_e is the power emitted by one electron, n_{long} is the total number of electrons in the bunch, $b_h = \left|\sum_k \exp(-i2\pi h z_k/\lambda_{\mathrm{L}})\right| / n_{\mathrm{short}}$ is the bunching factor and z_k are positions of $n_{\mathrm{short}} \approx n_{\mathrm{long}}/1000$ coherently radiating electrons. With $n_{\mathrm{long}} = 2.4 \cdot 10^{10}$ for a bunch current of 10 mA at the DELTA storage ring described below, a bunching factor of $b_h = 0.03$ is sufficient to achieve a ratio of coherent and incoherent power $P_{\mathrm{short}}/P_{\mathrm{long}} > 10$, and no spatial separation is required. Since the bunching factor reduces exponentially with harmonic number, the incoherent background limits h to values well below 10.

A possible extension of CHG to shorter wavelengths is echo-enabled harmonic generation (EEHG) proposed in 2009 as an FEL seeding scheme [16] and employing two modulators and a radiator as shown in Fig. 1 (center). As shown in longitudinal phase space in Fig. 2 (a-d), a strong chicane following the first modulator results in a phase space pattern with stripes of nearly constant energy. A second energy modulation, followed by another chicane, creates a density modulation which, in contrast to CHG, contains higher Fourier components. First EEHG proof-of-principle experiments were performed at SLAC in the USA [17] and SINAP in China [18].

A NEW LASER-BASED SCHEME

The essence of the EEHG scheme is to create stripes of discrete energy in phase space, which translate into narrowly spaced longitudinal fringes when subjected to a second energy modulation and sheared by a chicane. However, the straight sections in most synchrotron light sources are not

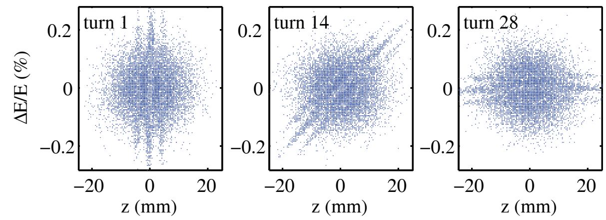

Figure 3: Distribution of electrons in phase space (energy offset in percent of the beam energy E versus longitudinal coordinate z), shown 1, 14 and 28 turns after a laser-induced energy modulation as shown in Fig. 2 (e).

long enough to accommodate three undulators with two chicanes between them. For the case of SOLEIL in France, a scheme with the two modulators in different straight sections was proposed [19] with the drawback of occupying two straight sections. Between them, nonlinearities and spurious r_{51} and r_{52} contributions tend to wash out the phase space pattern.

The scheme proposed in this paper aims at producing a pattern of discrete-energy stripes without using an additional modulator and chicane. For brevity, it will be denoted as discrete-energy coherent harmonic generation DECHG), where "discrete" refers to an energy width much smaller than the natural energy spread.

Here, the modulator of a CHG setup is used to create an energy modulation with periodically varying amplitude over a large fraction of the bunch, as shown in Fig. 2 (e). Energy-dependent path-length differences along the storage ring convert this pattern into discrete density maxima which turn into discrete-energy stripes after a quarter of a synchrotron period (Fig. 3). Next, a femtosecond laser pulse induces a second energy modulation in the same modulator followed by a chicane. This leads to microbunches separated by λ_{L} as in the case of CHG, but now with a number of density fringes within each microbunch. Effectively, each microbunch can be viewed as an image of the initial density distribution demagnified from the bunch length σ_{B} to a fraction of the laser wavelength. The rms length of the microbunches σ_{MB} is obtained by considering the triangle in Fig. 2 (g):

$$\Delta E \sin\frac{2\pi\sigma_{\mathrm{M}}}{\lambda_{\mathrm{L}}} \approx \Delta E \frac{2\pi\sigma_{\mathrm{M}}}{\lambda_{\mathrm{L}}} = \sigma_E \;\rightarrow\; \sigma_{\mathrm{M}} \approx \frac{\sigma_E}{\Delta E}\frac{\lambda_{\mathrm{L}}}{2\pi} \qquad (3)$$

with the amplitude ΔE of the second modulation given by Eq. 1. With a spacing of Δz between intensity maxima of the first laser pulse, the fringe spacing δz is then

$$\delta z = \Delta z \frac{\sigma_{\mathrm{M}}}{\sigma_{\mathrm{B}}} = \frac{\sigma_E}{\Delta E}\frac{\lambda_{\mathrm{L}}}{2\pi}\frac{\Delta z}{\sigma_{\mathrm{B}}} \qquad (4)$$

and the corresponding harmonic number is $h = \lambda_{\mathrm{L}}/\delta z$. The length of the coherent pulse emitted in the radiator is given by the second laser pulse of ultrashort duration. Alternatively, a longer laser pulse may be employed to produce pulses which are not ultrashort but exceed the pulse energy of conventional synchrotron radiation by orders of magnitude. Yet another option is to perform the second energy modulation with a

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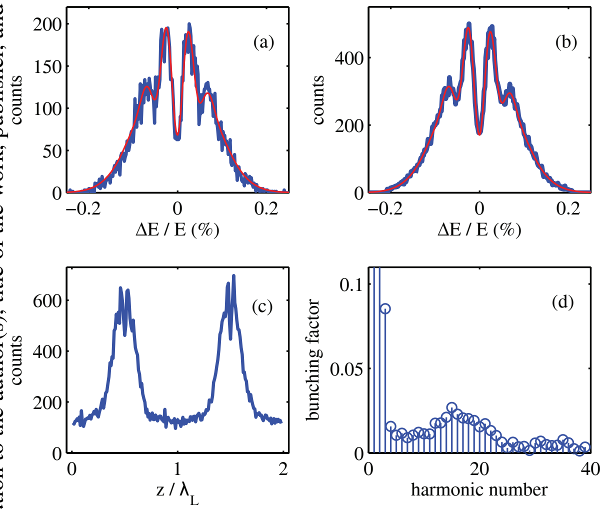

Figure 4: (a) Simulated energy distribution and fit function (red) at the bunch center after first energy modulation and 1/4 synchrotron period, (b) electron ensemble based on the fit function, (c) electron density after second energy modulation and chicane, and (d) bunching factor as function of harmonic number.

few-cycle pulse creating only one microbunch with fringes from the first modulation. In practice, however, it will be difficult to obtain $P_{\text{short}} > P_{\text{long}}$ with sub-femtosecond pulses due to the low number n_{short} of contributing electrons (see Eq. 2).

Although the scheme described here is new, each step is well-proven. The second energy modulation and microbunching corresponds to CHG. The first energy modulation using a long intensity-modulated laser pulse was demonstrated repeatedly at UVSOR in Japan [20] and later at DELTA [21] in order to produce tunable narrowband THz radiation. As shown in Fig. 1 (bottom), uncompressed and chirped pulses from a Ti:sapphire laser amplifier are split and recombined in a Michelson interferometer, and chirped pulse beating [22] creates an intensity modulation along the pulse.

A major concern for DECHG is that the striped phase space pattern may be washed out e.g. by energy diffusion due to incoherent synchrotron radiation (ISR). Electrons of energy E traveling a distance L through dipole magnets with a bending radius R acquire a relative energy spread (rms) given by [23]

$$\sigma_E[\text{keV}] \approx 6.4\ \text{keV} \cdot \sqrt{\frac{L[\text{m}]}{R^3[\text{m}^3]}} \cdot E^{7/2}[\text{GeV}^{7/2}]. \quad (5)$$

For the case of DELTA described next, $L = 560$ m and $R = 3.33$ m amounts to $\sigma_E = 103$ keV or 10% of the natural energy spread.

SIMULATION STUDY

DELTA is a 1.5-GeV synchrotron light source operated by the TU Dortmund University [24]. Although its parameters are not ideally suited for DECHG, its lattice serves as a test case for the following simulation study using a single-bunch current of 10 mA, a bunch length of 25 ps (rms) and a synchrotron frequency of 23 kHz (these parameters are valid after an RF upgrade in 2016). Assuming an intensity-modulated 800-nm laser pulse with a length of 11 ps (rms), a pulse energy of 30 mJ (commercially available with a repetition rate of 1 kHz), and $M_{\text{U}} = 7$ periods, 10^5 electrons were energy-modulated and tracked over 28 turns using the code *elegant* [25] including ISR. As shown in Fig. 4 (a), the resulting energy distribution of a central 1 mm thick bunch slice was fitted by a function describing a Gaussian distribution with equally spaced fringes. Based on the fit, a new ensemble of $5 \cdot 10^4$ electrons was created within a $2\lambda_{\text{L}}$ thick slice – see Fig. 4 (b) – and subjected to an energy modulation with a second laser pulse of moderate energy (a few mJ) and 20 fs (rms) duration.

The fringes within the microbunches cause a non-zero bunching factor for a group of harmonics around a value controlled by the amplitude of the second energy modulation. The chicane is then tuned to maximize the fringes. The smaller the spacing Δz of the intensity maxima of the first intensity-modulated laser pulse, the more fringes appear within each microbunch and the narrower is the group of enhanced harmonics. With $\Delta z = 5$ mm in the example shown here, the fringe spacing is 50 nm (cf. Eq. 4), and bunching factors of $b_h \approx 0.03$ are obtained at harmonics which cannot be reached by CHG, see Fig. 4 (c-d).

CONCLUSIONS

A drawback of DECHG is the fact that two laser pulses are needed with a time interval of several 10 μs between them, which requires a non-standard laser system or two independent laser amplifiers, one of them with a rather high pulse energy. A clear advantage of the method is to use a CHG setup with two undulators, which exists at several storage rings, in contrast to three undulators required for EEHG.

The bunching factor of $b_h = 0.03$ obtained for DELTA may be sufficiently large for a proof-of-principle experiment but not for routine operation. Better results can be obtained for optimized parameters such as a higher number of modulator periods and shorter bunches. Furthermore, the method favors a lower beam energy (reducing the ISR effect and improving the relative energy modulation), higher synchrotron frequency and larger bending radius (both reducing ISR).

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