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LASER SEEDING OF ELECTRON BUNCHES FOR FUTURE RING-BASED LIGHT SOURCES*

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Abstract

In contrast to free-electron lasers (FELs), ring-based light sources are limited in intensity by incoherent emission and in pulse duration by their bunch length. However, FEL seeding schemes can be adopted to generate intense and ultrashort radiation pulses in storage rings by creating laser-induced microbunches within a short slice of the electron bunch. Microbunching gives rise to coherent emission at harmonics of the seed wavelength. In addition, terahertz (THz) radiation is coherently emitted. At the 1.5-GeV electron storage ring DELTA, coherent harmonic generation (CHG) with single and double 40-fs pulses is routinely performed at seed wavelengths of 800 and 400 nm. Seeding with intensity-modulated pulses to generate tunable narrow-band THz radiation is also performed. As a preparation for echo-enabled harmonic generation (EEHG), simultaneous seeding with 800/400-nm pulses in two undulators has been demonstrated. In addition to short-pulse generation, steady-state microbunching at ring-based light sources will be discussed.

INTRODUCTION

Synchrotron light sources based on electron storage rings are and will continue to be the workhorses to investigate the structure of matter on the atomic scale with photons in the vacuum-ultraviolet (VUV) to X-ray range [1]. Over half a century, remarkable progress has been made regarding intensity in terms of photon flux and brilliance as well as stability of the photon beams. With the MAX IV facility in Lund/Sweden, another step was taken in reducing the horizontal beam emittance by introducing a 7-bend achromat lattice [2], and other facilities have upgrade plans in the same direction.

In contrast to conventional synchrotron light sources, free-electron lasers (FELs) achieve extremely high average and peak brillance by using electron beams from linear accelerators (linacs) and by microbunching which gives rise to coherent emission of radiation [3]. While the beam in a storage ring is subject to a long-term equilibrium between radiation excitation and damping, the electron bunches in a linac exist only for a few microseconds and retain the small emittance and bunch length with which they are produced. A bunch length being orders of magnitude smaller than in a storage ring implies a high peak current which makes high-gain FEL amplification possible. In addition, the short pulse length of emitted radiation allows to study the dynamics of matter with a temporal resolution in the femtosecond regime.

The spectral power of radiation emitted by n_e electrons at frequency ω is given by [4]

$$\begin{aligned} P(\omega) &= n_e^2 \cdot \left| \frac{1}{n_e} \sum_{j=1}^{n_e} e^{-i\omega t_j} \right|^2 \cdot P_e(\omega) \qquad (1) \\ &= n_e^2 \cdot b^2(\omega) \cdot P_e(\omega) \\ &= n_e \cdot P_e(\omega) + \left| \sum_{j}^{n_e} \sum_{k \neq k}^{n_e} e^{i\omega(t_j - t_k)} \right| \cdot P_e(\omega) \\ &= n_e \cdot P_e(\omega) + n_e(n_e - 1) \cdot g^2(\omega) \cdot P_e(\omega), \end{aligned}$$

where $P_e(\omega)$ is the spectral power emitted by one electron, $b^2(\omega)$ is the bunching factor and $g^2(\omega)$ is the so-called form factor. Thus, $P(\omega)$ is proportional to n_e for randomly distributed electrons as in storage rings but has a component proportional to n_e^2 if the longitudinal distribution has a significant Fourier contribution at frequency ω. As sketched in Fig. 1, this is achieved by structures of the order of the wavelength $\lambda = c/\omega$, either (i) by a sufficiently short bunch, (ii) by a short dip in the longitudinal distribution (iii) by an instability with fluctuations of the electron density, or most efficiently (iv) by periodic microbunching.

A storage ring with microbunched electrons would combine the high repetition rate and stability of SR sources with the high radiation power of an FEL. These benefits have already been demonstrated, e.g., in the coherent emission of terahertz (THz) radiation at storage rings in low-alpha operation where the bunch length can be reduced to the order of 1 ps [5]. However, this example also shows a limiting peculiarity of storage rings, namely the so-called longitudinal microwave instability (or turbulent bunch lengthening) which causes the bunch length to increase above a given threshold of the bunch charge.

For short-wavelength radiation, the periodic microbunching of a short fraction (a "slice") of a long electron bunch gives rise to coherent emission of an equally short radiation pulse which can be employed for time-resolved studies in pump-probe experiments where, e.g., a laser pulse excites the sample and a short-wavelength pulse probes its state as a function of the delay between the two pulses [6]. Here, the time resolution depends on the lengths of both pulses and on the stability of the delay.

Starting from a random electron distribution in longitudinal phase space, microbunching requires a manipulation of

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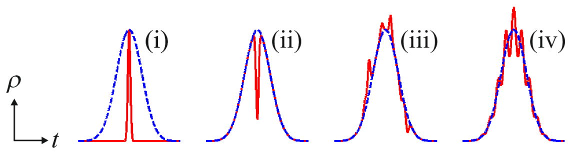

Figure 1: Longitudinal charge distributions (red) giving rise to coherent radiation at wavelengths shorter than the length of a standard bunch (blue). Left to right: a short bunch, a short dip, random fluctuations, periodic microbunching [6].

the longitudinal electron position via

$$\Delta z = r_{51} \cdot \Delta x + r_{52} \cdot \Delta x' + r_{56} \cdot \Delta E/E, \qquad (2)$$

where $(\Delta x, \Delta x')$ is the deviation in horizontal phase space, $\Delta E/E$ is the relative energy offset, and r_{5i} are the respective transfer matrix elements. Usually, the third term is employed by modulating the electron energy with a femtosecond laser pulse copropagating with the electrons in an undulator tuned to the laser wavelength (the "modulator"), which is followed by a sequence of dipole magnets (the "chicane") converting periodic energy modulation into microbunching. The other two terms of the equation tend to smear out the longitudinal structure and must be suppressed. Bunching by different velocities of the electrons is negligible with electron energies in the GeV range. Bunching by wake fields and by FEL amplification from random noise is also unlikely in storage rings due to the low charge density (compared to linac beams). The techniques to produce a microbunched slice within a storage ring bunch by laser-induced energy modulation are similar to those used for seeded FELs.

SHORT-PULSE GENERATION

Figure 2 shows different applications of laser-induced energy modulation in storage rings [6]. For an electron energy in the GeV regime, a laser pulse energy of several mJ is required which restricts the laser repetition rate to a few kHz. The undulator, from which the short pulses are emitted, is called "radiator".

In the femtoslicing scheme, off-energy electrons are transversely displaced by dispersion and their incoherently emitted synchrotron light passes an aperture while the radiation from the long bunch is blocked [7–11]. Here, no microbunching is employed and the radiation power is typically 10^{-4} of that from the whole bunch. The advantage of this scheme is that the radiator setting is independent of the seed wavelength and, despite the low photon flux, femtoslicing has been successful in producing scientific results.

Coherent harmonic generation (CHG) [12] is analogous to high-gain harmonic generation (HGHG) in seeded FELs [13], but without FEL gain. Periodic microbunching leads to coherent emission in a radiator set to a harmonic of the seed wavelength $\lambda_s = c/\omega_s$. Since the bunching factor decreases with $b^2(h \cdot \omega_s) \sim \exp(-h^2)$ with harmonic number h, only low harmonics (typically $h \leq 5$) fulfill the condition that the power ratio of coherently emitted radiation from n_{short}

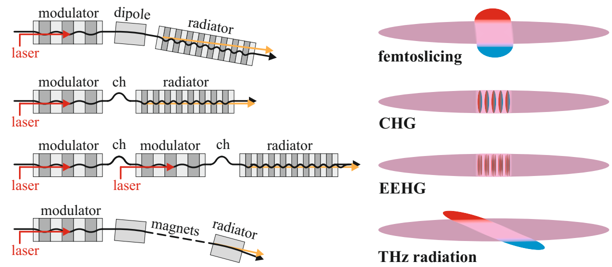

Figure 2: Short-pulse schemes making use of laser-induced energy modulation [6]. See text for details.

electrons in the slice and radiation from $n_{\text{long}} \approx 10^3 \cdot n_{\text{short}}$ electrons in the remaining bunch

$$\frac{P_{\text{short}}}{P_{\text{long}}} = \frac{n_{\text{short}}^2 \, b_h^2}{n_{\text{long}}} = f^2 \, n_{\text{long}} \, b_h^2 \quad \text{with} \quad f \equiv \frac{n_{\text{short}}}{n_{\text{long}}} \qquad (3)$$

is significantly larger than unity. In the 1980s, CHG was demonstrated with relatively long laser pulses (12 ps) [14]. As a short-pulse scheme with femtosecond laser pulses, CHG was performed at UVSOR in Okazaki/Japan [15], Elettra near Trieste/Italy [16], and more recently at DELTA in Dortmund/Germany [17].

Echo-enabled harmonic generation (EEHG) has been proposed as a scheme for FEL seeding but may also be employed for microbunching in storage rings [18]. Here, a twofold laser-induced energy modulation creates a more complex density modulation allowing to reach higher harmonics with $b^2(h \cdot \omega_s) \sim h^{-1/3}$, where the combination of two energy modulation amplitudes and two chicane settings has to be tuned for each harmonic individually. EEHG has been demonstrated at NLCTA/SLAC in Menlo Park/USA [19], reaching the 75th harmonic of a 2.4-µm seed without FEL gain [20], and at the SDUV-FEL/SINAP in Shanghai/China with first lasing showing exponential growth at the 3rd harmonic of 1.05-µm seed pulses [21]. As a short-pulse scheme for storage rings, EEHG was considered at SOLEIL in Saint-Aubin/France [22] and HLS in Hefei/China [23], but DELTA in Dortmund/Germany is presently the only storage ring with a funded EEHG program [24, 25].

Along the storage ring lattice, the off-energy electrons move ahead or lag behind, leaving a short dip in the longitudinal charge distribution which gives rise to the coherent emission of a short pulse of broadband THz radiation [26]. From turn to turn, the power of this radiation decreases and its spectrum shifts to the sub-THz regime as the dip increases in length and becomes more shallow [27]. Seeding with an intensity-modulated laser pulse produced by chirped-pulse beating leads to several equidistant dips and the coherent emission of narrowband far-infrared radiation. This has been demonstrated at UVSOR for radiation up to 700 GHz [28] and at DELTA in a frequency range from 1 to 5.5 THz [29].

The coherent emission of high harmonics in the EEHG scheme is based on the generation of a phase space distribution with small energy spread. Another method to this end was proposed in [30] using the fact that longitudinal dips

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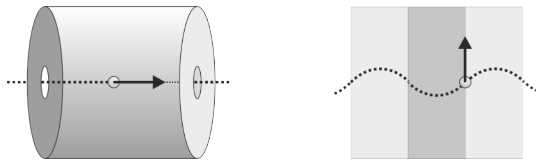

Figure 3: Sketch of an electron in an RF resonator (left) and copropagating with a laser pulse in an undulator (right). The dashed lines represent the electron path, the arrows indicate the force caused by the electric field of the RF wave or laser pulse, respectively (adapted from [31]).

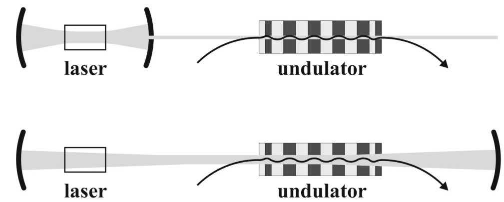

Figure 4: A light wave from a laser interacts with electrons in an undulator which may be outside (top) or inside (bottom) the optical cavity of the laser (adapted from [32]).

produced by an intensity-modulated laser pulse turns into energy stripes after a quarter of a synchrotron period. This effect has not yet been demonstrated because it requires two laser pulses with a delay of a few 10 μs which is not feasible with standard kHz-class laser systems.

STEADY-STATE MICROBUNCHING

The short-pulse schemes described above are based on standard laser technology, e.g., titanium:sapphire lasers with chirped-pulse amplification at a kHz repetition rate which is three orders of magnitude below the typical revolution frequency of storage rings. The objective of steady-state microbunching (SSMB) is the coherent emission of radiation at every turn which may either be achieved by sustained microbunching or by creating a longitudinal density modulation at each turn anew.

Low-alpha operation of storage rings [5] can be viewed as a type of sustained microbunching. The bunches are not narrowly spaced but the few-ps bunch length does support coherent far-infrared emission at every turn. Increasing the radiofrequency (RF) of a storage ring would reduce the spacing between the bunches as well as the bunch length. Lifetime and impedance issues may be mitigated by a reduced bunch charge while keeping the total beam current constant. Practical limitations arise from the reduced size of the RF resonators and the availability of continuous wave (cw) amplifiers. Here, a factor of 10 may be envisioned compared to the typical sub-GHz frequencies.

For higher frequencies, the RF resonator may be replaced by an undulator in which the electrons interact with a freely propagating electromagnetic wave (Fig. 3). This is the principle of laser-induced energy modulation discussed above. In contrast to the RF resonator, the electric field $\vec{\mathcal{E}}$ is not parallel but perpendicular to the electron velocity $\vec{v}$ which makes the interaction less efficient. The energy transfer is given by

$$\mathrm{d}E = -e\,\vec{\mathcal{E}}\cdot\vec{v}\,\mathrm{d}t = -e\left|\vec{\mathcal{E}}\right| x'\,c\,\mathrm{d}t, \tag{4}$$

where x' is the transverse angle of the electrons in the undulator. Its value in radian can be viewed as an efficiency factor compared to the resonator case. In principle, this scheme is capable of producing buckets in which the electrons are trapped similar to conventional RF buckets. Two cases may be considered as being not totally unrealistic: a cw far-infrared FEL with a wavelength of a few 100 µm and a CO_2 laser with 10 µm. A short-pulse scheme with a far-infrared FEL producing microbuckets in addition to conventional RF buckets has been proposed and a numerical example was given in [31]. As reported in [32], the electric field of a 10-kW cw CO_2 laser with a beam focused onto an area of 1 mm^2 amounts to $2.7\cdot10^6$ V/m. With a maximum angle of $x'_{\mathrm{max}} = K/\gamma = 10^{-2}$ rad (e.g., given by undulator parameter $K = 20$ and Lorentz factor $\gamma = 2000$), the energy transfer over a 4 m long undulator would be 50 keV, which is sufficient to compensate the electron energy lost per turn. Tighter focusing and/or placing the undulator inside a laser cavity (Fig. 4) would intensify the electric field significantly.

A sustained-microbunching scheme as described above would require a highly isochronous storage ring. While a sufficiently small momentum compaction factor (around 10^{-5}) can be realized, a path length variation of only a few µm would be still difficult to achieve. One reason is the betatron motion [33], another is the stochastic nature of synchrotron radiation [34]. These and other limitations may be overcome by novel lattice designs or by a combination of laser and RF techniques, where only a fraction of the electrons is trapped in microbuckets while others form a "coasting beam" within the larger RF buckets.

An energy and density modulation produced at each turn is an option for SSMB at visible wavelengths and beyond [35]. With progress in laser technology and by employing a laser cavity instead of a single-pass scheme, a sufficiently high repetition rate may be achieved. However, microbuncing at the full revolution frequency may not even be desirable from the user perspective. Apart from technical issues, the repetition rate of laser-induced energy modulation is limited by the tolerable energy spread. In the present kHz short-pulse schemes, about 10^{-3} of the electrons participate in the interaction with the laser pulses. With typically 10 laser pulses per longitudinal damping time, about 10^{-2} of the electrons are outside the natural energy distribution of the bunch. At a much higher repetition rate, it is necessary to reverse the modulation process turn by turn, i.e., first inverting the density modulation and then applying another laser-electron interaction with the opposite phase.

A storage ring driven by a far-infrared FEL, as described above, may be a useful machine to provide intense THz radiation simultaneously for multiple users whereas SSMB in the visible or near-infrared regime is of little interest for practical

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Table 1: Parameters of the DELTA Short-Pulse Facility

storage ring circumference	115.2 m
electron beam energy	1.5 GeV
beam current (single/multibunch)	20/130 mA
horizontal emittance	15 nm rad
relative energy spread (rms)	0.0007
bunch length (FWHM)	100 ps
laser wavelength	800 nm
min. laser pulse duration (FWHM)	40 fs
seed pulse energy at 800/400 nm	8.0/2.8 mJ
seed repetition rate	1 kHz
modulator/radiator period length	250 mm
number of modulator/radiator periods	7
undulator periods used as chicane	3
max. modulator/radiator K parameter	10.5
max. chicane r_{56} parameter	140 µm

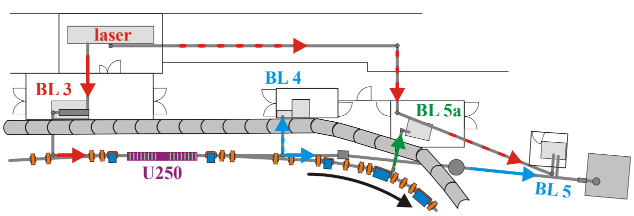

Figure 5: The short-pulse facility at DELTA comprising a laser system, a laser beamline (BL 3) guiding seed pulses to the undulator U250, a diagnostics beamline (BL 4), a soft X-ray beamline (BL 5), and a THz beamline (BL 5a).

applications. SSMB in the VUV or X-ray regime involves the task of converting the energy modulation provided by near-visible laser pulses into a density modulation that gives rise to the coherent emission of radiation at much shorter wavelengths, e.g., by employing an EEHG-like scheme that is performed and then reversed turn by turn.

THE SHORT-PULSE FACILITY AT DELTA

At the 1.5-GeV storage ring DELTA operated by the TU Dortmund University, CHG is routinely performed since 2011 [17] with up to 600 hours of beam time per year. The short-pulse facility (see Fig. 5 and Table 1) comprises a titanium:sapphire femtosecond laser system, a laser beamline, the undulator U250 in an optical-klystron configuration (modulator, chicane, radiator), a diagnostics beamline, a dedicated THz beamline, and a soft X-ray beamline operated by the Forschungszentrum Jülich/Germany. A telescope with lenses is employed to focus 800-nm pulses into the modulator while curved mirrors are used for seeding with frequency-doubled 400-nm pulses. The temporal overlap between laser pulses and spontaneous undulator radiation is established using a photodiode and a streak camera. The spatial overlap is found and optimized by visual inspection on a screen, followed by automated scanning of the last two laser mirrors while recording the THz signal.

CHG radiation with a minimum wavelength of 200 nm is characterized in air at the diagnostics beamline. Here, two Czerny-Turner-type spectrometers are employed, one measuring the radiation intensity with an avalanche photodiode while rotating a grating, the other recording single-shot spectra with a gated image-intensified CCD camera. For shorter wavelengths, the intensity and spectral distribution is determined using the plane-grating monochromator and photoelectron spectrometer of the soft X-ray beamline.

The spatial coherence of CHG radiation was studied by performing double-slit experiments with different slit separation. The temporal coherence length was determined using a Michelson interferometer and a double-slit setup with movable glass wedges to delay light from one slit with respect to the other. The temporal coherence length of the CHG pulses was found to be about three times longer than that of spontaneous undulator radiation [36]. Similar results were obtained by analyzing speckle patterns from CHG pulses passing through a diffuse organic film [37].

Laser seeding was also performed while modulating the RF phase of the storage ring cavity by twice the synchrotron frequency which is usually done to improve the beam lifetime [38]. By synchronizing the phase modulation with the laser pulses, microbunching is created at an electron density and energy spread which deviates significantly from equilibrium. The intensity of CHG pulses and coherently emitted THz radiation was found to increase by up to 30% depending on the modulation amplitude and phase as well as synchrotron frequency (tuned by changing the RF power).

The spectrotemporal properties of CHG radiation were studied under variation of the r_{56} value of the chicane between modulator and radiator and by introducing a laser chirp, i.e., a correlation between wavelength and position along the laser pulse [39]. The chicane setting controls the longitudinal distribution of microbunches while the chirp determines their spacing. Two groups of microbunches with equal spacing, as an example, give rise to interference fringes in the CHG spectrum.

First pump-probe experiments were performed probing the Cu(111) surface state by CHG pulses at 133 nm (the third harmonic of 400-nm seed pulses) showing a spectral shift of the photoelectrons due to Coulomb repulsion from the electron cloud induced by the laser pump pulse – see [40].

For the planned EEHG upgrade of the DELTA short-pulse facility, the hardware is funded and partly in house. Figure 6 shows the present CHG setup and a possible EEHG configuration. Replacing the 3- and 7-degree bending magnets by 10-degree magnets, a 20 m long straight section is created to accommodate three undulators and two chicanes. Two new electromagnetic undulators with a period length of 200 mm will be used as modulators while the present undulator U250 will be the radiator. In the present configuration, EEHG-like seeding was tested by performing a twofold laser-electron interaction of 400-nm pulses from second-harmonic generation (SHG) in one part of the undulator U250 and with the residual 800-nm pulses in the other part. The interaction of both pulses with the same electrons was verified by

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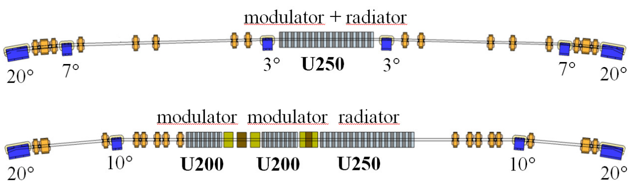

Figure 6: Present CHG configuration (top) and possible setup for EEHG (bottom) at the DELTA storage ring.

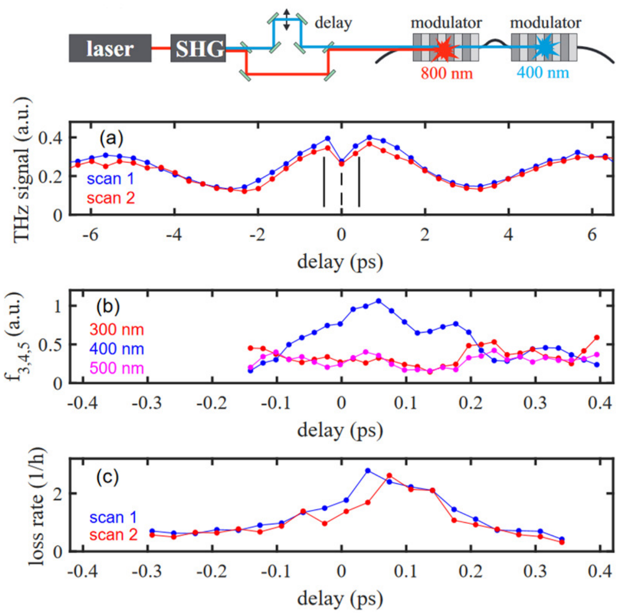

Figure 7: Seeding with 800- and 400-nm pulses in two modulators. Three quantities are shown as functions of delay between the two pulses: (a) THz radiation intensity, (b) Fourier coefficients of the THz signal for a delay variation in sub-wavelength steps, (c) beam loss rate [41].

different effects. The THz signal depends on the delay between the pulses and shows a dip indicating a reduction of the number of coherently emitting electrons at zero delay (Fig. 7a). Within the dip, the THz signal is sensitive to the relative phase of the two pulses as evidenced by a Fourier analysis (Fig. 7b). A twofold energy modulation results in a larger energy offset leading to an increased loss rate when the storage ring is operated with low RF power (Fig. 7c).

CONCLUSIONS

Seeding of electron bunches with laser pulses results in a periodic energy modulation which is converted to microbunching by the r_{56} matrix element of a chicane and gives rise to the coherent emission of radiation at a wavelength corresponding to the microbunch spacing or harmonics thereof. The emitted power is proportional to the number of contributing electrons squared which can either be used to generate radiation of very high intensity or to control the length, shape, and spectral properties of the coherently emitted pulses. Examples are the coherent emission of far-infrared pulses and the CHG scheme to generate ultrashort pulses in the VUV regime. For scientific applications, it is important to access shorter wavelengths by circumventing the limiting effect of the energy spread on the length of the microbunches. One possibility is EEHG involving a twofold laser-electron interaction, another is to compress the microbunches by introducing a correlation between the electron energy and a transverse coordinate ("cooled CHG", e.g., [42–45]).

At the DELTA short-pulse facility, CHG as well as the coherent emission of THz radiation is routinely performed since 2011. The implementation of EEHG is planned requiring a modification of 1/4 of the storage ring.

Using mJ laser pulses, the repetition rate of CHG or EEHG is presently limited to the kHz range. The ultimate dream is the coherent emission of short-pulse radiation at a much higher rate, possibly at every turn, combining the radiation power of FELs with the repetition rate of storage rings. Driving a storage-ring beam in a steady-state fashion by a laser rather than an RF wave can be envisioned at long wavelengths using powerful infrared FELs or lasers but is limited by the achievable isochronicity of the ring. Steady-state microbunching at shorter wavelengths can, in principle, be accomplished by laser seeding at every turn which, however, will require further progress in laser technology.

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