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SEEDING OF ELECTRON BUNCHES IN STORAGE RINGS*

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Abstract

Seeding schemes for free-electron lasers (FELs) can be adopted to generate ultrashort radiation pulses in storage rings. Creating laser-induced microbunches within a short slice of a long electron bunch gives rise to coherent emission at harmonics of the seed wavelength. In addition, THz radiation is produced over many turns. Even without FEL gain, a storage ring is an excellent testbed to study many aspects of seeding schemes and short-pulse diagnostics, given the high repetition rate and stability of the electron bunches. At DELTA, a 1.5-GeV electron storage ring operated by the TU Dortmund University in Germany, coherent harmonic generation (CHG) with single and double 40-fs seed pulses is performed at wavelengths of 800 nm or 400 nm. As a preparation for echo-enabled harmonic generation (EEHG), simultaneous seeding with 800 and 400 nm pulses in two different undulators is performed and several techniques are employed to ensure optimum timing between the seed pulses.

INTRODUCTION

Seeding of high-gain free-electron lasers (FELs) with external radiation pulses allows to control and improve spectrotemporal properties of FEL pulses at short wavelengths [1]. In electron storage rings, seeding methods can be adopted to generate femtosecond radiation pulses emitted by a short "slice" within a several 10 ps long electron bunch [2]. For pump-probe applications, another advantage of external seeding is the natural synchronization between two pulses, i.e., the seed pulse, from which a fraction is used to pump a sample, and the probe pulse resulting from the seeding process. The basic seeding mechanism is a periodic modulation of the electron energy induced by the electric field of a laser pulse co-propagating with the electrons in an undulator (the "modulator").

In an FEL seeding scheme known as "high-gain harmonic generation" (HGHG) [3], a magnetic chicane converts the energy modulation into a periodic density modulation ("microbunching") which gives rise to FEL gain at harmonics of the seed pulse wavelength in a second undulator (the "radiator"). Presently, FERMI (Trieste, Italy) is the only HGHG-seeded FEL in user operation [4]. The bunching factor and thus the efficiency of the seeding process decreases exponentially with increasing harmonic order. One method to reach shorter wavelengths is to use the resulting FEL pulse as seed for a second modulator. This two-stage (or cascaded) HGHG process has been demonstrated at FERMI [5]. Another method to obtain FEL gain at shorter wavelengths is "echo-enabled harmonic generation" (EEHG) involving a twofold laser-induced energy modulation to generate a density pattern with high harmonic content [6]. EEHG has been studied at NLCTA (SLAC, Menlo Park, USA) [7, 8] and at SDUV-FEL (SINAP, Shanghai, China) [9].

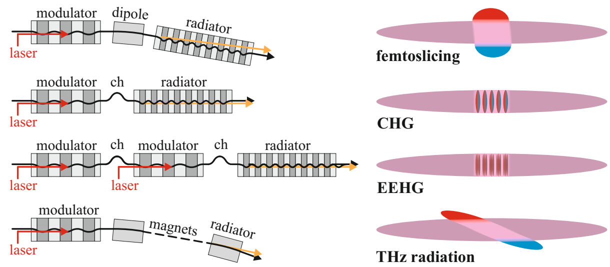

Figure 1: Applications of laser-induced energy modulation in storage rings. Left: Magnetic layout with undulators and chicanes (ch). Right: Resulting electron bunch structure (red and blue: electrons with energy gain and loss).

SEEDING IN STORAGE RINGS

In storage rings, the energy modulation induced by a femtosecond laser pulse applies to ≈ 1/1000 of the bunch length and can be employed in several ways (see Fig. 1).

After passing a dipole magnet, the off-energy electrons are transversely displaced and emit a short off-axis pulse of synchrotron radiation in an undulator tuned to any wavelength [10]. Since the electrons are not microbunched, the pulse energy is proportional to the number of electrons and about 10^{-4} times lower than the energy emitted from the whole bunch. This scheme, known as "femtoslicing", has been demonstrated at ALS (LBNL, Berkeley, USA) [11] and is employed in user operation at BESSY (Berlin, Germany) [12], SLS (PSI, Villigen, Switzerland) [13], and SOLEIL (Saint-Auban, France) [14].

Similar to HGHG, microbunching with a chicane causes coherent emission of radiation at harmonics of the seed wavelength. Without FEL gain, this process is called "coherent harmonic generation" (CHG) and was first demonstrated with ps laser pulses at ACO (Orsay, France) [15]. Short-pulse generation via CHG was performed at UVSOR (Okasaki, Japan) [16], ELETTRA (Trieste, Italy) [17], and DELTA (Dortmund, Germany) [18]. Due to coherent emission, the pulse energy is proportional to the number of electrons squared. Even for 1/1000 of the electrons in the bunch, the CHG pulse energy exceeds that of incoherent

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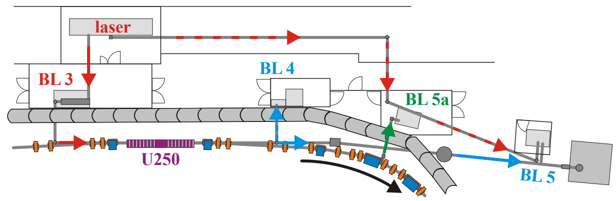

Figure 2: The short-pulse facility at DELTA comprising a laser system, a laser beamline (BL 3) guiding seed pulses to the undulator U250, a diagnostics beamline (BL 4), a soft-X-ray beamline (BL 5), and a THz beamline (BL 5a).

emission from the whole bunch. The accessible wavelengths are restricted to low harmonics ($h < 10$). Employing the EEHG scheme to reach smaller wavelengths with coherent emission in storage rings was studied for SOLEIL [19] and DELTA [20]. Performing a twofold energy modulation at successive turns was proposed for HLS (Heifei, China) [21].

In the storage ring lattice, the energy-dependence of the path lengths causes energy-modulated electrons to leave a gap in the longitudinal charge distribution which gives rise to broadband coherent emission in the (sub-)THz regime over several turns. This radiation serves as diagnostics for the laser-induced energy modulation [22] and provides information on the electron dynamics in the ring [23]. Seeding with ps intensity-modulated laser pulses allows to generate tunable narrowband THz radiation [24, 25].

Many aspects of FEL seeding can be studied in a storage ring. With a MHz revolution frequency, the laser-electron interaction rate is only limited by the laser system. Another benefit is the excellent beam stability. For a typical beam lifetime, the relative turn-by-turn decrease of the bunch charge is below 10^{-10}. Given the low electron density, space charge effects are usually negligible. Radiation damping provides stability and a homogeneous slice emittance and energy spread but also limits the freedom in manipulating the bunches. For a given radiofrequency (RF) voltage and momentum compaction factor, the bunch length is fixed and no static energy chirp can be applied. However, dynamic changes of the electron distribution can be introduced by modulating the RF phase [26] or by driving an instability.

THE SHORT-PULSE FACILITY AT DELTA

At the 1.5-GeV electron storage ring DELTA, operated by the TU Dortmund University as a synchrotron light source [27], about 50 days per year of dedicated beam time are available for seeding studies. Parameters of the ring and the CHG short-pulse facility [18] are given in Table 1. The setup is shown in Fig. 2.

Seed pulses from a titanium:sapphire laser system are focused directly through a beamline (BL 3) into the electromagnetic undulator U250 or are frequency-doubled first. The 7 upstream/downstream periods of the U250 act as modulator/radiator for CHG with a chicane between them. A diagnostics beamline (BL 4) is used to observe the spatial overlap of laser and undulator radiation on screens and to establish

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

the temporal overlap using a streak camera. CHG radiation is characterized in air down to wavelengths of 190 nm. A soft-X-ray beamline (BL 5) operated by the Forschungszentrum Jülich is equipped with a plane-grating monochromator and a hemispherical photoelectron spectrometer. For pump-probe experiments, an evacuated beamline sends a fraction of each laser pulse to the BL 5 endstation. A dedicated beamline for THz radiation from a dipole magnet [28] is equipped with several detectors and spectrometers.

SPECTROTEMPORAL MANIPULATION

As shown in [29] for the case of FERMI, the spectrotemporal properties of HGHG/CHG pulses can be controlled by the chirp of the seed pulses and the parameter r_{56} of the magnetic chicane. Similar measurements at DELTA have been reported [30, 31]. At early experiments, CHG spectra were recorded using an avalanche photodiode while rotating the grating of a Czerny-Turner monochromator over several minutes. More recently, a gated image-intensified camera (iCCD) was used to record single-shot spectra allowing for scans of the chicane current from 0 to 700 A (r_{56} = 140 μm) in 1-A steps within a similar period of time.

For 800 nm seeding, spectra of the second and third harmonic are shown in Fig. 3 for two different compressor settings of the laser amplifier. At large r_{56} values, microbunching occurs for electrons having interacted with the head and tail of the seed pulse while electrons with maximum energy modulation are overbunched. Consequently, unchirped seed pulses result in CHG spectra with interference fringes corresponding to two successive pulses. In the case of a strong chirp, the spectra exhibit two peaks at the frequencies of the seed pulse head and tail.

The spectrotemporal properties of pulses emerging from the laser amplifier were determined using frequency-resolved optical gating (FROG) [32]), measuring a minimum pulse duration of 42 fs (FWHM) for unchirped pulses. However, these properties are not only influenced by the

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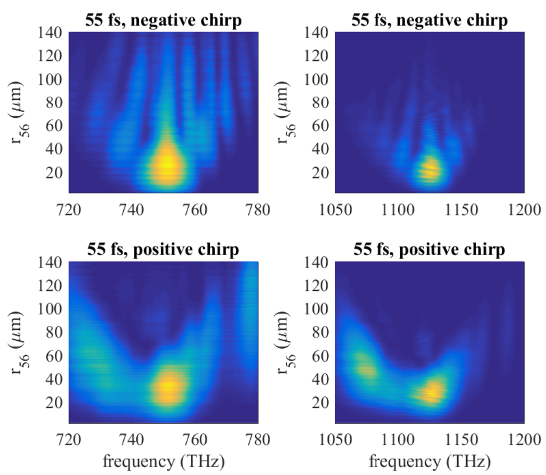

Figure 3: CHG spectra of the second (left) and third harmonic (right) of 800 nm seed pulses with negative chirp (top) and positive chirp (bottom), both with a pulse length of 55 fs, under variation of the chicane strength r_{56}.

stretcher-compressor configuration but also by the transition of the pulses through air and glass (lenses and vacuum window). Therefore, CHG spectra of pulses with 55 fs duration and negative chirp show pronounced interference fringes at large r_{56} values whereas this is not the case for pulses with similar duration and positive chirp. The asymmetry of the CHG spectra is an indication of higher-order chirp.

SEEDING WITH DOUBLE PULSES

A future application of the EEHG scheme at DELTA [20] will require a twofold energy modulation of the same electrons. To this end, first double-pulse seeding experiments were conducted (see Fig. 4). One example is seeding with two 800 nm pulses in the same modulator as described in [33], another is seeding in different modulators which corresponds to the EEHG configuration without second chicane and radiator [34]. In the latter case, one 400 nm pulse is produced by second harmonic generation (SHG), the other pulse is the residual 800 nm radiation after the SHG process. Both pulses are focused and steered independently to optimize the transverse overlap with the electron bunches. The temporal laser-electron overlap is obtained by shifting the RF input controlling the laser oscillator timing with a vector modulator. The timing between the two pulses is tuned by moving mirrors on a linear stage and fine-tuned on the sub-fs level by changing the chicane current. The delay introduced by the chicane between the two modulators is $\Delta t = r_{56}/(2c)$ with c being the speed of light. Three methods were used to verify the temporal overlap (see Fig. 5):

(1) The THz signal as function of delay shows a symmetric interference pattern. A dip at the central maximum indicates that both radiation pulses act on the same part of the bunch thus reducing the number of electrons participating in coherent THz emission.

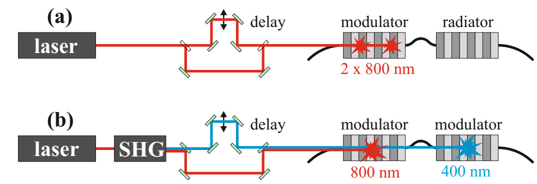

Figure 4: Seeding with 800 nm double pulses in the same modulator (a) and with 800 and 400 nm pulses in two modulators (b) with variable delay.

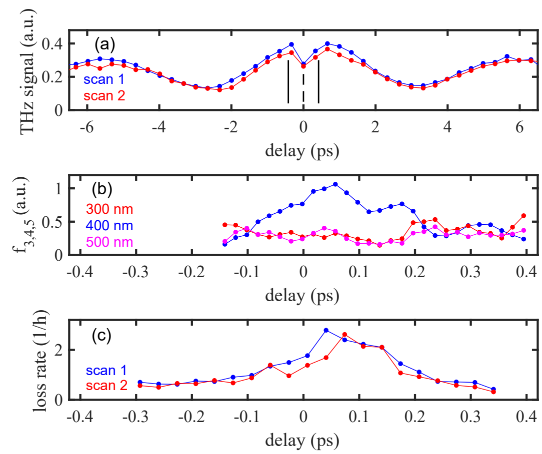

Figure 5: THz radiation (a), Fourier coefficients of the THz signal for few-fs delay variation (b), and beam loss rate (c) as function of the delay between 800 and 400 nm seed pulses. Zero delay and the delay range of (b,c) is defined in (a).

(2) Only when both pulses act on the same electrons, the energy modulation is sensitive to their relative phase. As explained in [34], the THz signal exhibits a modulation with a periodicity of 400 nm when scanning the chicane-induced delay over several fs.

(3) A twofold energy modulation of the same electrons results in a larger energy offset for some electrons. When reducing the RF power and thus the energy acceptance of the storage ring, the temporal overlap is indicated by an increased beam loss rate (reduced beam lifetime).

This way, an EEHG-like energy modulation can be performed and verified without radiator. In summary, spectrotemporal manipulation and double-pulse seeding were discussed as examples to show that FEL seeding methods can be studied at a storage ring benefiting from its high revolution frequency and stability. Features which are not available at linear accelerators – such as multiturn coherent THz emission and the beam loss rate – provide additional diagnostics opportunities.

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