CHARACTERIZATION OF LASER-ELECTRON INTERACTION AT THE BESSY FEMTOSLICING FACILITY *

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Abstract

A "femtoslicing" facility to generate ultrashort x-ray pulses by laser-electron interaction is being commissioned at the BESSY II storage ring. The energy modulation of electrons by femtosecond laser pulses is a good test case for FEL seeding schemes. The dependence of the interaction efficiency on various parameters is discussed.

INTRODUCTION

A laser pulse co-propagating with an electron bunch in an undulator modulates the electron energy if the resonance condition

$$\lambda_\mathrm{L} = \frac{\lambda_U}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \tag{1}$$

is fulfilled. Here, λ_L is the laser wavelength, λ_U is the undulator period, γ is the Lorentz factor of the electrons, and K is the undulator field parameter. The oscillatory energy modulation has a period length equal to λ_L and an envelope corresponding to the laser pulse shape enlarged by $\lambda_L\, N_U$, the slippage of the electrons relative to the laser field over N_U undulator periods.

Laser-induced energy modulation has a number of promising applications, among them seeding of a free-electron laser (FEL), either by high-gain harmonic generation (HGHG) [1] or by sideband seeding [2]. Energy modulation is the basic mechanism for "femtoslicing" [3, 4] and various proposals for sub-femtosecond pulse generation, e.g. [5]. Another idea is to generate coherent-light replica of electron bunches for diagnostics purposes [6]. Periodic energy modulation of electrons by a femtosecond laser pulse leads to:

– transverse displacement due to dispersion, which is the desired effect in the context of femtoslicing,

– the formation of microbunches for small differences (below $\lambda_L/2$) of the energy-dependent electron path length, emitting coherent radiation at a fraction of λ_L, particularly at higher harmonics of the laser, as in HGHG,

– a dip in the longitudinal electron distribution for path length differences exceeding the laser pulse length, giving rise to coherent radiation in the THz regime.

At the BESSY II storage ring, a femtoslicing source to generate x-ray pulses of 50 fs (fwhm) duration is currently being commissioned [7, 8]. Its purpose is to study ultrafast structural and magnetic changes in matter, and to gain experience in view of BESSY's soft-x-ray FEL project [9]. As a test case for FEL seeding schemes, femtoslicing allows to study the dependence of the energy modulation efficiency on various parameters. Relevant electron beam parameters are the electron energy (or Lorentz factor), the beam size given by emittance, beta functions and dispersion, and the energy spread. The laser properties of interest are the laser wavelength, bandwidth, chirp, polarisation, pulse energy and duration, as well as beam size and divergence, which in turn depend on λ_L and the quality parameter M^2. The undulator is specified by the period length, the number of periods, and to first order by the magnetic field parameter K, but higher harmonics of the field may also be relevant. The interaction efficiency depends critically on the overlap of laser and electrons in all phase space dimensions, i.e. horizontal and vertical position and angle, longitudinal coordinate (timing) and spectral overlap according to eq. 1.

The amplitude of the energy modulation ΔE is in principle given by [3]

$$(\Delta E)^2 = 4\pi\alpha A_L E_L \frac{K^2/2}{1+K^2/2}\frac{\Delta\omega_L}{\Delta\omega_U}\,, \tag{2}$$

where α is the fine structure constant, A_L is the pulse energy, E_L is the photon energy, and K is the undulator parameter. The bandwidth ratio $\Delta\omega_L/\Delta\omega_U$ of laser and undulator radiation is roughly given by $N_U/N_L \le 1$, the ratio of undulator periods and optical cycles in the laser pulse (if $N_U > N_L$, the electron slippage exceeds the laser pulse length and there is no further gain). There are corrections for matching laser and undulator spectra, and for the finite electron beam size [4], but the dependence on other parameters has to be studied by numerical simulation or experimentally, as discussed below.

FEMTOSLICING – PRINCIPLE AND IMPLEMENTATION AT BESSY II

The principle of femtoslicing involves energy modulation of electrons in an undulator ("modulator") by a short laser pulse, followed by transverse displacement in order to extract the short-pulse component of radiation emitted in a subsequent undulator. At BESSY II, the modulator U-139 (a planar wiggler with $\lambda_U = 139$ mm, $N_U = 10$) and radiator UE-56 (an elliptical undulator with $\lambda_U = 56$ mm, $N_U = 30$) are both placed in the same straight section to

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minimize pulse lengthening. The energy-modulated electrons are displaced by angles upto 1 mrad such that their radiation does not overlap with the radiation from the bunch core, which can be blocked by an aperture without using imaging elements, which would cause a large background due to non-specular scattering. A liquid-nitrogen cooled Ti:sapphire laser system [10] provides pulses at a wavelength of $\lambda_L = 800$ nm with a pulse energy up to 2.8 mJ at 1 kHz (alternatively 1.8 mJ at 2 kHz). Further details of the technical implementation at BESSY are given in the caption of fig. 1 and elsewhere [7].

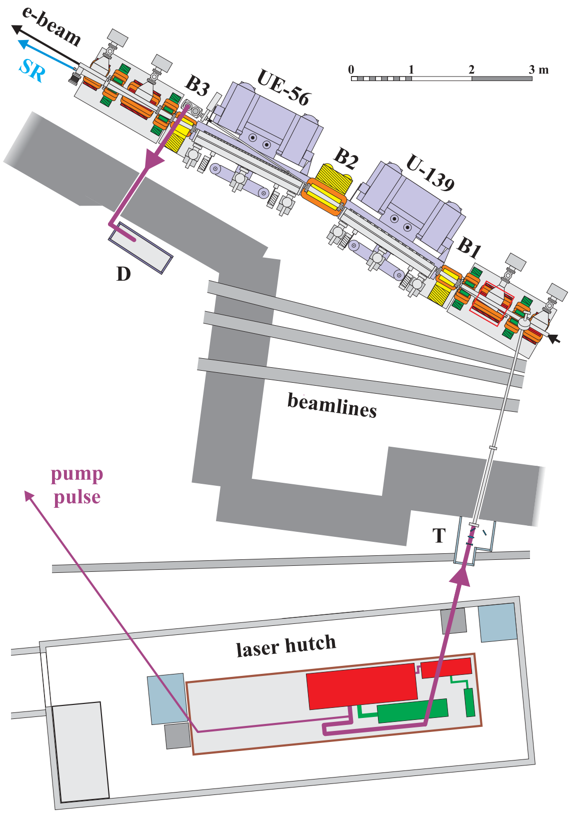

Figure 1: Overview of the femtoslicing facility. A laser hutch outside the storage ring tunnel houses a Ti:sapphire oscillator and amplifier (red) with respective pump lasers (green). The main pulse is focussed by a telescope (T) and enters the storage ring vacuum, while a small fraction will be sent as a pump pulse to the experiment. Modulator (U-139) and radiator (UE-56) are within a chicane formed by three bending magnets B1 (3.32°), B2 (6.40°) and B3 (3.08°). Laser and U-139 radiation are directed to a diagnostics station (D) above the storage ring tunnel.

NUMERICAL SIMULATIONS

Prior to the construction of the femtoslicing facility at BESSY II, numerical simulations were employed to determine the laser requirements (such as pulse energy, pulse duration and M^2), to study the effects of imperfect electron-laser overlap and other deviations from an ideal situation, and to devise a suitable separation scheme for the short-pulse x-ray component. The generation of a realistic distribution of energy-modulated electrons allows to predict the shape of the dip causing THz radiation emission as well as properties of the short x-ray pulses such as photon rate, background, spatial distribution and spectral characteristics.

The laser-induced energy deviation ΔE is modelled by integrating the product of the horizontally transverse electron velocity x' and the electric field $\mathcal{E}$ over the length $L = N_U \lambda_U$ of the modulator

$$\Delta E = -e \int_{-L/2}^{L/2} x'(s)\, \mathcal{E}(x,y,z)\, ds \tag{3}$$

for an ensemble of randomly generated "macro-electrons". The electric field of the laser pulse is given by

$$\mathcal{E}(x,y,z) = \sqrt{2\rho(x,y,z)/\varepsilon_\circ}\, \sin\left[2\pi z/\lambda_L - \varphi_G(z)\right] . \tag{4}$$

Here, $\varepsilon_\circ$ is the permittivity of free space, φ_G is the Guoy phase shift [11], and (x, y, z) is the electron position relative to the laser pulse, where z changes by one laser wavelength λ_L for each undulator period. The laser pulse is assumed to be Gaussian with an energy density ρ. While the pulse length is constant, the transverse rms size depends on the position s_L of the laser pulse relative to the waist position $s_\circ$ and on the beam quality factor M^2:

$$\sigma_{x,y}(s_L) = \sqrt{\sigma^2_{x,y}(s_\circ) + \left(\frac{M^2\lambda_L}{4\pi\sigma_{x,y}(s_\circ)}\right)^2 (s_L - s_\circ)^2} . \tag{5}$$

Modifications of the laser field in this low-gain process are assumed to be small and are not included in the model.

The result of the simulation is the amount of energy acquired by each macro-electron in the interaction process and the energy-modulation "profile", i.e. the electron distribution along the ΔE-axis. The endpoint of that distribution is the modulation amplitude, which – for a realistic simulation – is systematically lower than given by eq. 1. Another useful quantity is the number of electrons exceeding a certain energy offset. For femtoslicing at BESSY II, for example, radiation from electrons with $\Delta E/E > 0.7\%$ is assumed to be separable.

EXPERIMENTAL METHODS

Successful electron energy modulation at a femtoslicing facility can be verified by various means, including

(1) cross-correlation of visible synchrotron radiation from transversely displaced electrons with laser pulses,

(2) measurement of the spectral dependence of the laser gain as a function of K, i.e. the single-pass FEL gain,

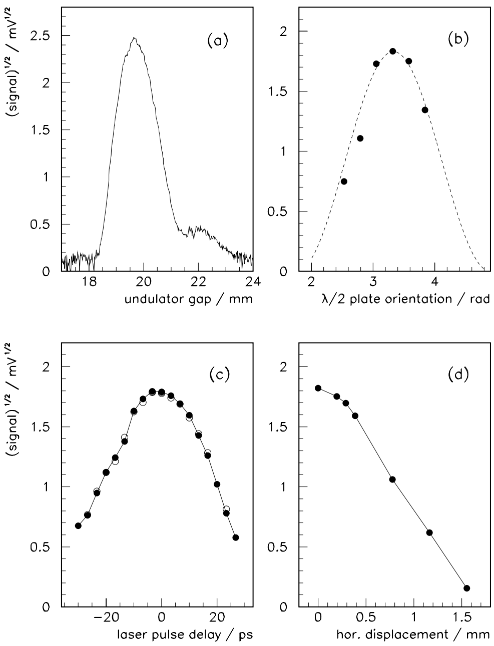

Figure 2: Square root of the THz signal, locked to the laser repetition frequency of 998 Hz, as function of (a) the undulator gap, (b) the orientation of a half-wave plate, where the dashed line indicates a $\sin^2$-dependence, (c) the longitudinal laser position and (d) horizontal misaligment with 0.33 mm corresponding to the rms electron beam size.

(3) detection of THz radiation from a dip in the longitudinal bunch profile,

(4) scraping transversely displaced electrons and measuring the electron loss rate,

(5) observation of synchrotron radiation from transversely displaced electrons,

(6) observation of enhanced radiation due to microbunching.

Methods (1) and (2), employed at the pioneering experiments described in [4], were not yet applied to the BESSY case, because method (3) offers very sensitive and simple on-line diagnostics, once THz detection is available. At BESSY II, a dedicated THz beamline with a fast infrared bolometer was constructed [12], and examples are presented below. THz diagnostics indicates the occurrence of energy modulation and allows to optimize its efficiency, but does not directly measure the modulation amplitude. The transverse displacement of electrons is proportional to their energy modulation and can be measured by methods (4) and (5), where (4) is very simple but destructive, whereas (5) involves the rather complex synchrotron radiation emission characteristics. Method (6), finally, is not easily realized in a storage ring and has not yet been attempted.

THz Diagnostics

The radiation power emitted by an electron distribution $\varrho(z)$ for a given photon wave number $1/\lambda$ is

$$P(1/\lambda) = N\,p_{1/\lambda} + f_{1/\lambda}\,N\,(N-1)\,p_{1/\lambda}\,, \qquad (6)$$

where $p_{1/\lambda}$ is the power emitted by a single electron, N is the number of electrons, and $f_{1/\lambda}$ is a form factor linked to the electron distribution via Fourier transform:

$$f_{1/\lambda} = \left| \int e^{i2\pi z/\lambda}\,\varrho(z)\,dz \right|^2 . \qquad (7)$$

When path length differences of energy-modulated electrons exceed the laser pulse length, a hole is created in the longitudinal electron distribution, giving rise to a large form factor around $1/\lambda \sim 100$ cm^{-1}, i.e. coherent radiation in the THz regime.

At BESSY II, THz radiation from a dipole magnet is routinely employed to detect laser-induced energy modulation and to optimize the spatial, temporal and spectral laser-electron overlap. The dependence of the THz signal, locked to the laser repetition rate of 998 Hz, on several critical parameters is shown in figure 2.

In part (c) of the figure, the square root of the signal is directly proportional to the electron density. Otherwise, quantitative conclusions regarding the energy modulation are not easily drawn from the THz spectrum. A model-dependent comparison would include the electron dynamics between modulator and the location of the THz beamline, application of eq. 7 to the resulting electron distribution, and consideration of the detector bandwidth.

Scraper Measurements

The energy modulation $\Delta E/E$ at a position with optical functions β_x, α_x, γ_x, dispersion D and $D' = dD/ds$ excites a horizontal betatron oscillation. With a scraper positioned at a distance Δx from the beam center, electrons contribute to the loss rate (i.e. the inverse beam lifetime) if

$$\Delta x \leq \Delta E/E \sqrt{\beta_x^{\rm S}} \sqrt{\gamma_x D^2 + 2\alpha_x DD' + \beta_x D'^2}\,, \quad (8)$$

where the horizontal beta function is $\beta_x^{\rm S}$ and the dispersion is zero at the location of the scraper. The top part of figure 3 shows the beam lifetime while the scraper is moved towards the beam and the laser is blocked periodically. The scraper position relative to the beam center is deduced from the position at which the quantum lifetime becomes dominant, as shown in the bottom part of figure 3. The solid line is derived from a simulated energy-modulation profile, where ideal overlap was assumed and the laser pulse energy was varied to match the data. The resulting pulse energy was about half the value measured at the laser exit, indicating power losses or insufficient overlap at the time of the experiment.

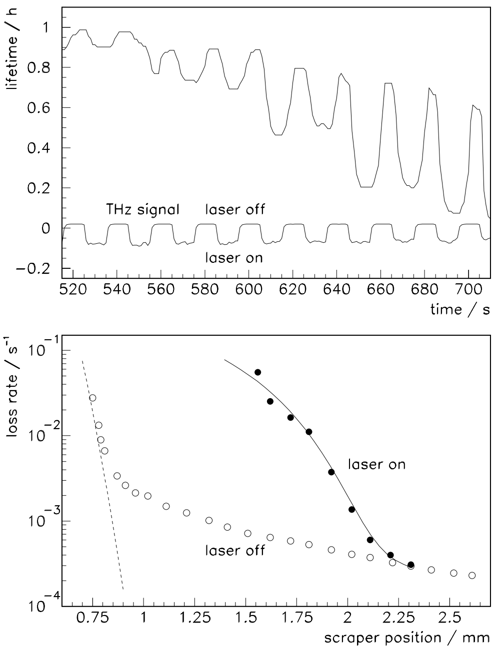

Figure 3: Top – beam lifetime versus time while a scraper is moved towards the beam and the laser is blocked periodically. Bottom – loss rate versus scraper position. The dashed line indicates the quantum lifetime limit, the solid line is a simulation result.

Synchrotron Radiation from Displaced Electrons

The purpose of femtoslicing is to generate short radiation pulses from electrons transversely displaced in the radiator. Figure 4 shows the photocurrent from a GaAs diode behind the exit slit of a monochromator, which was recorded while an aperture in the frontend was moved across the radiation distribution of the UE-56 radiator and the laser was blocked periodically. With laser-induced energy modulation, the average photocurrent is enhanced even though the single-bunch rate is 1250 times larger than the laser repetion rate. This is due to the fact, that the transverse displacement of an energy-modulated electron is maintained over many turns, given by the longitudinal and transverse damping time, and radiation from the same electron is detected many times, depending on the energy-modulation profile and the observation angle. The time-integrated measurement is a simple method to detect the presence of energy modulation, while a quantitative measurement requires:

– selection of a fast detector signal at the interaction time to exclude radiation from successive turns or from other electron bunches,

– pulse height analysis to detemine the number of simultaneously arriving photons,

– interaction with the same bunch only after one or two radiation damping times to exclude radiation from electrons excited at previous interactions.

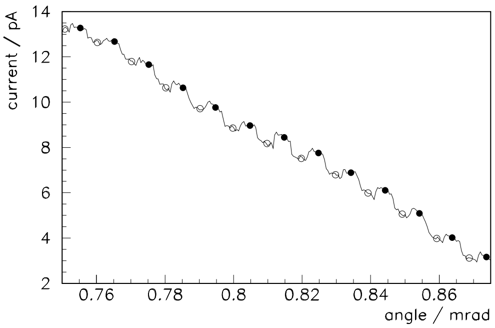

Figure 4: Angular distribution of undulator radiation at 707 eV recorded with a GaAs photodiode while the laser is blocked periodically. With laser (black symbols), the photocurrent is enhanced even though the laser repetition rate is only 1 kHz, while the electron bunch rate is 1.25 MHz.

Experiments to this end are in preparation. Until then, quantitative conclusions rely on scraper measurements during dedicated shifts, while THz diagnostics remains the best everyday tool for optimization.

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