A NOVEL DIAGNOSTICS OF ULTRASHORT ELECTRON BUNCHES BASED ON DETECTION OF COHERENT RADIATION FROM BUNCHED ELECTRON BEAM IN AN UNDULATOR

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Abstract

We propose a new method for measurements of the longitudinal profile of 100 femtosecond electron bunches for X-ray Free Electron Lasers (XFELs). The method is based on detection of coherent undulator radiation produced by modulated electron beam. Seed optical quantum laser is used to produce exact optical replica of ultrashort electron bunches. The replica is generated in apparatus which consists of an input undulator (energy modulator), and output undulator (radiator) separated by a dispersion section. The radiation in the output undulator is excited by the electron bunch modulated at the optical wavelength and rapidly reaches a hundred-MW-level power. We then use the now-standard method of ultrashort laser pulse-shape measurement, a tandem combination of autocorrelator and spectrum (FROG – frequency resolved optical gating) providing real-time single-shot measurements of the electron bunch structure. The big advantage of proposed technique is that it can be used to determine the slice energy spread and emittance in multishot measurements. We illustrate with numerical examples the potential of the proposed method for electron beam diagnostics at the European X-ray FEL.

INTRODUCTION

The past decade has been tremendous progress in the development of electron accelerators that produce ultrashort bunches approaching sub-100 femtosecond durations [1]. The use of ultrashort electron bunches for both fundamental studies and applications is increasing rapidly, too [2]. As electron bunches shrink in length and grow in utility, the ability to measure them becomes increasingly important. There are several reasons for this. First, precise knowledge of the bunch properties is necessary for verifying theoretical models of bunch creation [3]. Second, in order to make even shorter bunches, it is necessary to understand the distortions that limit the length of currently available pulses. Third, in experiments using these bunches, it is always important to know at least the pulse length in order to determine the temporal resolution of a given experiment. Moreover, in many experiments – studies of X-ray SASE FELs, for example - additional details of the bunch structure play an important role in determination of the outcome of the experiment. Of particular importance is the variation of peak current, emittance and energy spread along the bunch. Finally, numerous applications have emerged for emittance-shaped ultrashort electron bunches and, of course, it is necessary to be able to measure the emittance, or energy spread shape of the electron bunch used in these experiments [4].

The new principle of diagnostic techniques described bellow offers a way for full characterization of ultrashort electron bunches [5]. It is based on a construction of an exact optical replica of an electron bunch.

OPTICAL REPLICA SYNTHESIS

A basic scheme of the optical replica synthesizer and optical replica of a complex test electron bunch is shown in Fig. 1 [5]. A relatively long laser pulse is used to modulate the energy of electrons within the electron pulse at the seed laser frequency. The electron pulse will be timed to overlap with the central area of the laser pulse. The duration of the laser pulse is much larger than the electron pulse time jitter of a fraction of ps, so it can be easily synchronized with the electron pulse. The laser pulse serves as a seed for modulator which consists of a short undulator and dispersion section. Parameters of the seed laser are: wavelength 1047 nm, energy in the laser pulse 1 mJ, and FWHW pulse duration 10 ps. The laser beam is focused onto electron beam in a short (number of periods is equal to $N_\mathrm{w} = 5$) modulator undulator resonant at the optical wavelength of 1047 nm. Optimal conditions of focusing correspond to the positioning of the laser beam waist in the center of the modulator undulator. The size of the laser beam waist is 10 times larger than the electron beam size. The seed laser pulse interacts with the electron beam in the modulator undulator and produces an amplitude of the energy modulation in the electron bunch of about 250 keV. Then the electron bunch passes through the dispersion section (momentum compaction factor is about of $R_{56} \simeq 50\mu$m) where the energy modulation is converted to the density modulation at the laser wavelength. The density modulation reaches an amplitude of about 10%. Following the modulator the beam enters the short (number of periods is equal to $N_\mathrm{w} = 5$) radiator undulator which is resonant at laser (or double) frequency. Because the beam has a large component of bunching, coherent emission is copiously produces by the electron bunch. The bandwidth-limited output radiation pulse (see Fig. 2) has 10 μJ-level pulse energy and is delivered in a diffraction-limited beam.

The optical replica synthesizer is expected to satisfy certain requirements which can be achieved by suitable design

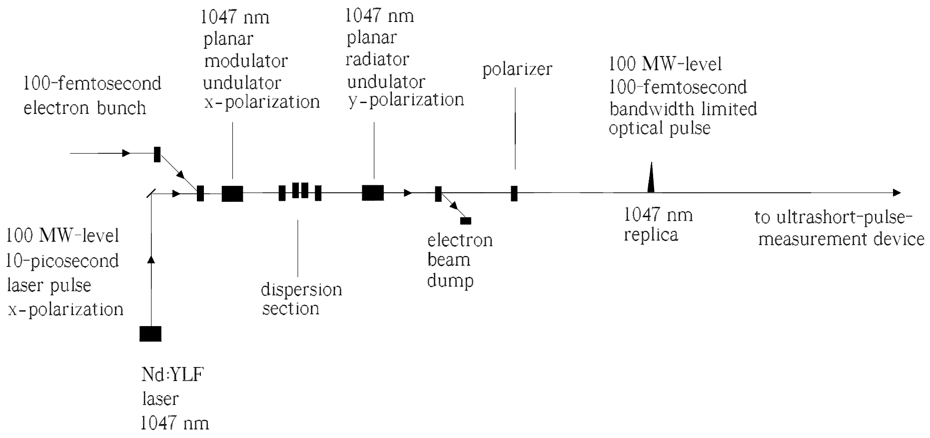

Figure 1: Schematic diagram of the optical replica synthesis through optical modulation of electron bunch and coherent radiation in the output undulator. Signal beam filter based on polarizer: y-polarized light is transmitted, while x-polarized light is reflected

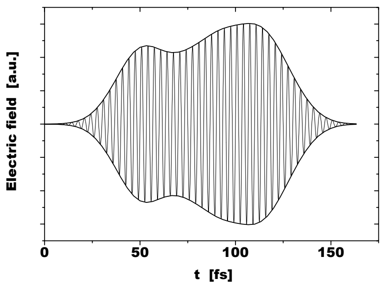

Figure 2: Optical replica (rapidly oscillating curve) of a test electron bunch. Radiator operates at the wavelength of 1047 nm

and choice of the components. A complete optimization of the proposed diagnostic device can be performed only with three-dimensional time-dependent numerical simulation code. Numerical results presented in this paper are obtained with version of code FAST [6] modified for simulation of optical replica synthesis. This code allows one to perform simulations of coherent undulator radiation taking into account all physical effects influencing the synthesizer operation.

One important point in the construction of replica synthesizer is separation of the optical replica from the seed laser pulse. Numerous designs are possible – for example, the combination of two planar undulators placed in crossed positions, as it is illustrated schematically in Fig. 1. In another scheme a frequency doubler can used to distinguish the optical replica from the intense seed laser pulse. when input undulator operates at a seed frequency, and an output undulator operating at a multiple of this frequency.

When propagating in vacuum, the radiation field is faster than the electron beam, and it moves forward (slips) by one wavelength, λ, per one undulator period, $\lambda_{\rm w}$. It is clear that the resolution of the electron pulse shape is determined by the slippage of the radiation with respect to electrons in the output undulator. If the slippage time is much less than the electron pulse duration, $N_{\rm w}\lambda/c \ll \tau_{\rm e}$, then one can neglect the slippage effect.

MEASUREMENT OF ELECTRON CURRENT PROFILE

The study and detailed understanding of the cause and nature of collective effects is important for successful design of replica synthesizer. Proposed design is conducted to eliminate collective effects as much as possible through installation of short input and output undulators. The signal produced by replica synthesizer is thus a pulse of electric field amplitude:

$$E(t) = F(I(t), \epsilon_{\rm n}(t), \Delta\mathcal{E}(t)) = I(t) f(\epsilon_{\rm n}(t), \Delta\mathcal{E}(t)) \ ,$$

where $\epsilon_{\rm n}(t)$ is the normalized slice emittance and $\Delta\mathcal{E}(t)$ is the slice energy spread in the electron bunch. If longitudinal beam dynamics in the synthesizer is governed by purely single-particle effects then this field directly proportional to the peak current $I(t)$.

Within the scope of the electrodynamic theory the output characteristics of the replica synthesizer are controlled by three dimensional parameters: $\lambda, \quad L_{\rm w}, \quad \sigma$, where λ is the radiation wavelength, $L_{\rm w} = N_{\rm w}\lambda_{\rm w}$ is the radiator undulator length, and σ is the electron beam transverse size.

At an appropriate normalization of electrodynamic equations, the coherent undulator radiation is described by only one dimensionless parameter [5]:

$$N = 2\pi\sigma^2/(\lambda L_{\mathrm{w}}) \ .$$

The parameter N can be referred to as the electron beam Fresnel number, or as diffraction parameter. In general case the electric field of the wave radiated in the undulator depends on the transverse size of the electron beam. For a proposed diagnostic technique it is of great interest to minimize the influence of the transverse emittance on the radiation field amplitude. In the case of a wide electron beam

$$\lambda L_{\mathrm{w}} \ll 2\pi\sigma^2 \ , \qquad \text{or} \quad N \gg 1 \ , \tag{1}$$

the most of the radiation overlaps with electron beam and field of the wave is inversely proportional to the square of electron beam [5]:

$$E(t) \propto I(t)/\sigma^2(t) \ .$$

Reducing the particle beam cross-section by diminishing the betatron function reduces also the size of the radiation beam and increases the total power of output radiation. This process of reducing the beam cross-section is, however, effective only up to some point. Further reduction of the particle beam size would practically no effect on the radiation beam size and total radiation power because of diffraction effects (see Section 4). In the limit of a thin electron beam the transverse radiation beam size tends to the constant value and the dependence of the output radiation on the transverse size of the electron beam is rather weak. The boundary between these two asymptotes is about $\sigma^2 \simeq \lambda L_{\mathrm{w}}$.

From the preceding discussion we may want to optimize the beam geometry as follows. The transverse size of the electron beam has to be much smaller then the diffraction limited radiation beam size

$$\sigma^2 \ll \lambda L_{\mathrm{w}}/(2\pi) \ , \qquad \text{or} \quad N \ll 1 \ , \tag{2}$$

The radiation wavelength and the undulator length dictate the choice of the optimum transverse size of the electron beam. Let us present a specific numerical example. Suppose $\gamma = 10^3$, $\epsilon_{\mathrm{n}} = 2\pi\mu$m, $\lambda_{\mathrm{w}} = 6.5$ cm, $N_{\mathrm{w}} = 5$, $\lambda = 1\mu$m. If the focusing beta function is equal to 1 m the diffraction parameter is $N = 2\pi\sigma^2/(\lambda L_{\mathrm{w}}) \simeq 0.04$. We come to the conclusion that we can treat this situation as a coherent undulator radiation generated by a thin electron beam. This condition may be easily satisfied in practice.

Proposed design is conducted to eliminate emittance effects as much as possible through installation of a special electron beam focusing system. In the radiator undulator the betatron function should reach small values (of about 1 m) forming a narrow beam waist. The signal generated by a replics synthesizer is thus a pulse of electric field with amplitude:

$$E(t) = F(I(t), \epsilon_{\mathrm{n}}(t), \Delta\mathcal{E}(t)) = I(t) f(\Delta\mathcal{E}(t)) \ .$$

Optimum parameters of the dispersion section can be estimated in the following way. The expression for the fundamental component of the bunched beam current is $i_1(t) = 2I(t)J_1(X)$, where $X = 2\pi R_{56}\delta\mathcal{E}/(\lambda\mathcal{E}_0)$ is dimensionless quantity known as the bunching parameter, $\delta\mathcal{E}$ is the amplitude of energy modulation induced in the modulator undulator. The function $J_1(X)$ approaches $X/2$ for small X; thus the microbunching approaches $i_1(t) \simeq XI(t)$. We see that microbunching depends on the choice of the dispersion section strength. One might think that all we have to do is to get microbunching amplitude to maximum – we can always increase R_{56} of the dispersion section and we can always increase output power. It is not impossible to build dispersion section that has large R_{56} function. In fact, one of the main problems in the modulator operation is preventing the spread of microbunching due to local energy spread in the electron beam. For effective operation of replica synthesizer the value of suppression factor should be close to unity. To get a rough idea of the spread of electron density modulation, the position of the particles within the electron beam at the dispersion section exit has a spread which is equal to $\Delta z' \simeq R_{56}\Delta\mathcal{E}/\mathcal{E}_0$, where $\Delta\mathcal{E}$ is the local energy spread in the electron bunch. We know that uncertainty in the phase of the particles is about $\Delta\psi \simeq 2\pi\Delta z'/\lambda$. Therefore, a rough estimate for the microbunching spread to be small is

$$2\pi R_{56}\Delta\mathcal{E}/\mathcal{E}_0 \ll 1 \ . \tag{3}$$

The result of more careful analysis (see Section 3) shows that in our case the optimal condition can be written as $X \simeq 0.1$, $\delta\mathcal{E} \simeq \max(\Delta\mathcal{E})/3 \simeq 250$ keV. The amplitude of energy modulation dictates the choice of the seed laser parameters. In our case the optimal peak power of the seed laser is about of 100 MW.

In general, radiation field depends on the peak current, $I(t)$, local energy spread, $\Delta\mathcal{E}(t)$, and local emittance, $\epsilon_{\mathrm{n}}(t)$. However, under conditions of a thin electron beam (2) and of a microbunching spread to be small (3), the electric field of the wave radiated in the replica synthesizer is directly proportional to the peak current of the electron beam:

$$E(t) = F(I(t), \epsilon_{\mathrm{n}}(t), \Delta\mathcal{E}(t)) = \mathrm{const.} \times I(t) \ .$$

Thus, conditions (2) and (3) should be treated as optimal tuning of undulator length, strength of the dispersion section and focusing beta function for measurement of the electron bunch profile.

MEASUREMENT OF SLICE EMITTANCE AND ENERGY SPREAD

We found that longitudinal profile of the electron bunch $I(t)$ can be reconstructed on the basis of a single-shot measurements. The next problem is determination of slice

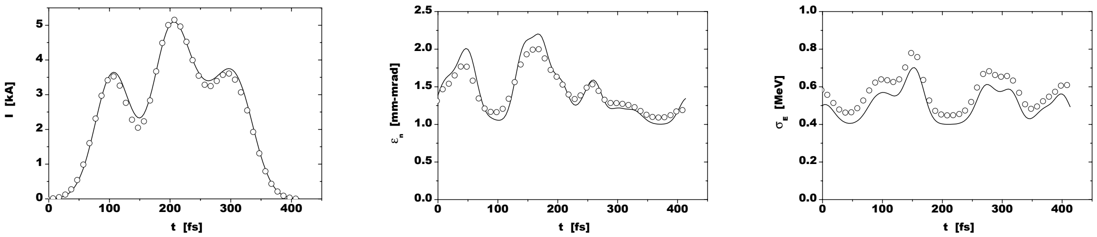

Figure 3: Target (solid curve) and retrieved (circles) electron beam peak current, slice emittance and slice energy spread. The nominal energy of electrons is equal to $\mathcal{E}_0 = 500$ MeV. Number of undulator periods is equal to $N_\mathrm{w} = 5$. The optical replica is generated at the radiation wavelength 1047 nm. Calculations were performed with code FAST.

energy spread ($\Delta\mathcal{E}(t)$) and slice emittance ($\epsilon_\mathrm{n}(t)$). This can be done on the basis of multishot measurements. If the electron pulse shape, $I(t)$, is known, the local energy spread $\Delta\mathcal{E}(t)$ can be determined from the dispersion section strength scan. In this way, the problem of slice energy spread measurement is transformed into a relatively simple task of measuring the radiation field amplitude maximum ($\max E(t) \propto \max i_1(t)$). An attempt to increase of the amplitude of the fundamental harmonic, by increasing the strength of dispersion section, is countered by decrease the energy spread suppression factor. In Section 3 we demonstrate that the microbunching $i_1(t)$ has clearly a maximum

$$\max i_1(t) = \mathrm{const.} \times \delta\mathcal{E}[I(t)/\Delta\mathcal{E}(t)] \ ,$$

and the optimum strength of the dispersion section is

$$R_{56} = \frac{\lambda\mathcal{E}_0}{2\pi\Delta\mathcal{E}(t)} \ .$$

Thus, measuring the $\max E(t)$ is strictly equivalent to measuring the local energy spread variations along the electron bunch: $I(t)/[\max E(t)] = \mathrm{const.} \times \Delta\mathcal{E}(t)$. Since the optimal strength of the dispersion section is known, that of the unknown absolute value of slice energy spread, $\Delta\mathcal{E}(t)$, is easily found too.

Slice emittance can be measured in the following way. Let us consider for illustration of the method a simple model of the electron bunch, assuming that slice emittances are different, but Twiss parameters are the same in all slices (more general model is discussed in section 5). The solution in our case is to realize that in a wide electron beam asymptote (1) the most of the radiation overlaps with the electron beam and the field of the wave is inversely proportional to the square of the electron bunch, $E(t) \propto I(t)/\sigma^2(t)$. If the electron pulse shape, $I(t)$, is known, the problem of the slice emittance measurement is transformed into a simple task of measuring the radiation field amplitude in the case of a wide electron beam

$$I(t)/E(t) = \mathrm{const.} \times \sigma^2(t) \quad \mathrm{as} \quad \min(\sigma^2) \gg \lambda L_\mathrm{w}/(2\pi) \ .$$

Since the value of beta function and projected emittance are known (from a standard method using a screen and quadrupole scan), then the unknown absolute value of slice emittance $\epsilon_\mathrm{n}(t)$ is easily determined, too.

In Fig. 3 we illustrate retrieval of the slice bunch properties from the optical replica of the electron bunch. Numerical calculations were performed using code FAST. The nominal energy of electrons is equal to $\mathcal{E}_0 = 500$ MeV. Number of undulator periods in the modulator and radiator undulator is equal to $N_\mathrm{w} = 5$. Period length is 6.5 cm. The optical replica is generated at the radiation wavelength 1047 nm. The seed laser power is 100 MW, FWHM pulse duration is 10 ps. Upper plots in Fig. 3 show comparison of target and reconstructed values for the beam current. When taking these data, parameters for the numerical experiment were set according to conditions (2) and (3): focusing beta function in the radiator is 1 meter, and net compaction factor of the dispersion section is 50 μm. Calculations show that pulse energy in the optical replica exceeds 30 μJ. Slice energy spread was determined by means of the scan of dispersion section strength at the value of beta-function of 1 meter (lower plots in Fig. 3). The values of slice emittance were extracted with the help of additional set of calculations with large value of beat function of 50 m which corresponds to the limit of a wide electron beam. We see that slice bunch properties can be retrieved with high accuracy if optical replica can be characterized with high accuracy.

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