COHERENT OPTICAL TRANSITION RADIATION AS A TOOL FOR ULTRASHORT ELECTRON BUNCH DIAGNOSTICS

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Abstract

In this contribution we describe how Coherent Optical Transition Radiation can be used as a diagnostic tool for characterizing electron bunches in X-ray Free-electron lasers. The proposed method opens up new possibilities in the determination of ultrashort, ultrarelativistic electron bunch distributions. Our technique is described more extensively in [1], where the interested reader will also find relevant references.

INTRODUCTION

Operational success of XFELs will be related to the ability of monitoring the spatio-temporal structure of sub-100 fs electron bunches as they travel along the XFEL structure. However, the femtosecond time-scale is beyond the scale of standard electronic display instrumentation. Therefore, the development of methods for characterizing such short electron bunches both in the longitudinal and in the transverse directions is a high-priority task, which is very challenging.

A method for peak-current shape measurements of ultrashort electron bunches using the undulator-based Optical Replica Synthesizer (ORS), together with the ultrashort laser pulse shape measurement technique called Frequency-Resolved Optical Gating (FROG) was recently proposed (see references in [1]). It was demonstrated that the peak-current profile for a single, ultrashort electron bunch could be determined with a resolution of a few femtoseconds. The ORS method is currently being tested at the Free-electron laser in Hamburg (FLASH). Novel results will be reported at this conference.

In this paper we present a feasibility study for integrating the ORS setup with a high-resolution electron bunch imager based on coherent Optical Transition Radiation (OTR). Our ideas are discussed in detail in [1], where the interested reader will also find relevant references that are omitted here for reasons of space.

Electron bunch imagers based on incoherent OTR constitute the main device presently available for the characterization of an ultrashort electron bunch in the transverse direction. They work by measuring the transverse intensity distribution. Since no fast enough detector is presently available, the image is actually integrated over the duration of the electron bunch. Therefore, incoherent OTR imagers fail to measure the temporal dependence of the charge density distribution within the bunch. For these reasons, the use of standard incoherent OTR imagers is limited to transverse electron-beam diagnostics, to measure e.g. the projected transverse emittance of electrons. However, it is primarily the emittance of electrons in short axial slices, which determines the performance of an XFEL. Therefore, there is a need for electron diagnostics capable of measuring three-dimensional (3D) ultrashort electron bunch structures with micron-level resolution.

The main advantages of coherent OTR imaging with respect to the usual incoherent OTR imaging is in the coherence of the radiation pulse, and in the high photon flux. Exploitation of these advantages leads to applications of coherent OTR imaging that are not confined to diagnostics of the transverse distribution of electrons. The novel diagnostics techniques described here can be used to determine the 3D distribution of electrons in a ultrashort single bunch. In combination with multi-shot measurements and quadrupole scans, they can also be used to determine the electron bunch slice emittance.

The possibility of single-shot, 3D imaging of electron bunches with microscale resolution makes coherent OTR imaging an ideal on-line tool for aligning the bunch formation system at XFELs. In order to ensure SASE lasing at X-ray wavelengths, a very high orbit accuracy of a few microns has to be ensured in the 200 m long undulator. The resolution of incoherent OTR imagers is not adequate to characterize the position of the center of gravity of an electron bunch with such accuracy. Our studies show that coherent OTR imaging can be utilized as an effective tool for measuring the absolute position of the electron bunch with the required micron accuracy. Finally, the improvement of bunch-imaging techniques up to the microscale level does not only yield a powerful diagnostics tool, but opens up new possibilities in XFEL technology as well.

OPTICAL REPLICA SETUP

We propose to create a coherent pulse of optical radiation by modulating the electron bunch at a given optical wavelength and by letting it pass through a metal foil target, thus producing coherent OTR at the modulation wavelength. The radiation pulse should be produced in such a way to constitute an exact replica of the electron bunch. Reference [1] includes a discussion about how to avoid the influence of self-interaction effects. The optical replica can be used for the determination of the 3D structure of electron bunches. Although other projects may benefit from our study too, throughout this paper we will mainly refer to parameters and design of the European XFEL.

In order to produce the optical replica we need to modulate the electron bunch at a fixed optical wavelength. One may take advantage of an Optical Replica Synthesizer

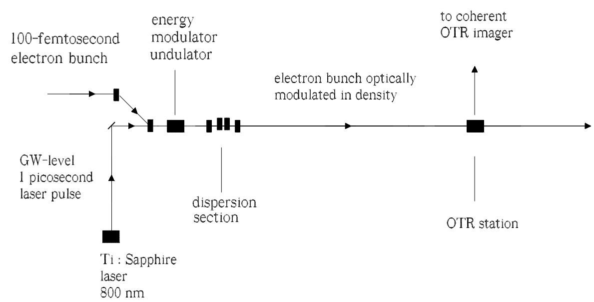

Figure 1: Schematic diagram of the coherent imager. The working principle is based on the optical modulation of the electron bunch and on emission of coherent OTR radiation from the metallic mirror.

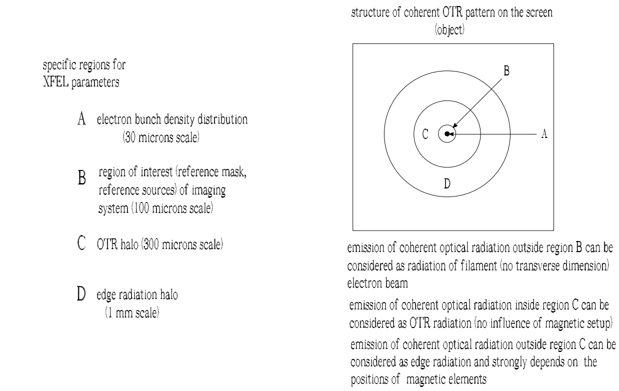

Figure 2: Scheme of the coherent OTR radiation pattern as observed in the object plane for the low electron beam energy case of 2 GeV.

(ORS) modulator, which we suppose to be installed after the BC2 bunch compressor chicane. A basic scheme to generate coherent OTR is shown in Fig. 1.

A relatively long laser pulse serves as a seed for the modulator, consisting of a short undulator and a dispersion section. The central area of the laser pulse should overlap with the electron pulse. In order to ensure simple synchronization, the duration of the laser pulse should be much longer than the electron pulse time jitter, which is estimated to be of order 100 fs. Foreseen parameters of the seed laser are: wavelength $\lambda_m = 800$ nm, energy in the laser pulse 1 mJ and pulse duration (FWHM) 1 ps. The laser beam is focused onto the electron bunch in a short (the number of periods is $N_w = 5$) modulator undulator resonant at the optical wavelength of 800 nm. Optimal conditions of focusing are met by positioning the laser beam waist into the center of the modulator undulator, with a Rayleigh length of the laser beam equal to the undulator length. Since the electron betatron function β, the undulator length L_w and the Rayleigh length of the laser beam are of the same magnitude, the size of the laser beam waist turns out to be about 20 times larger than the electron beam size. As a consequence, we can approximate the laser beam with a plane wave when discussing about the modulation of the electron bunch. 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 500 keV. Subsequently, the electron bunch passes through the dispersion section (with momentum compaction factor $R_{56} \simeq 50\mu$m), where the energy modulation is converted into density modulation at the laser wavelength. The electron bunch density modulation reaches an amplitude of about 10%. Finally, the modulated electron bunch travels through the OTR screen. It should be mentioned that OTR screens can be positioned at various locations down the electron beam line where electrons have substantially different energies. In the case of the European XFEL, the electron energy varies from 2 GeV (second bunch compression chicane) up to 17.5 GeV at the undulator entrance. For other machines, these parameters differ. In the case of LCLS, energies will range from about 4.5 GeV to 13.6 GeV.

THE OTR SOURCE

A powerful burst of OTR is emitted, which contains coherent and incoherent parts. The coherent OTR has much greater number of photons, up to 10^{13} i.e. 1μJ per pulse. A detailed study shows that, in our case of interest, we can exploit the Ginzburg-Frank formula for the characterization of the OTR field from a single electron at the OTR screen. Then, the field distribution for the electron bunch at the OTR screen in the space-frequency domain is essentially a convolution in the space domain of the temporal Fourier transform of the charge density distribution and the temporal Fourier transform of the single-electron field. Qualitatively, we can distinguish between four zones of interest, Fig. 2. Information about the electron bunch will be shown to be included in a small region of size $\sigma_r \sim 30\mu$m, region A. The region of interest of the imaging system is characterized by $r < 100\ \mu$m, region B. The field distribution for $100\ \mu\text{m} < r < 300\ \mu$m does not depend on the transverse size of the electron beam, region C. Finally, the position of magnetic structures become relevant at larger distances $r \sim 300\ \mu\text{m} \sim \gamma\lambda/(2\pi)$, region D.

COHERENT OTR IMAGING

The so called $4f$ filtering architecture is ideal for a coherent OTR imaging setup, Figure 3. We demonstrate that such setup can be used to characterize electron density profiles on the microscale level. Such resolution level can be reached by spatially filtering in the Fourier plane and using a radial-to-linear polarization conversion. In this way, the particle spread function is improved up to the point spread function for a point-like source.

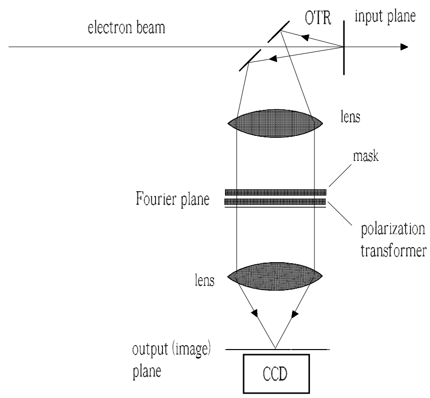

Figure 3: A practical arrangement of the coherent OTR image-processing system. (The hole in the OTR screen is for simplicity of drawing only. A tilted configuration should be used at these wavelengths instead.)

DIFFRACTIVE IMAGING METHODS

Diffractive imaging is one of the most promising techniques for microscale imaging of electron bunches, when a detector records the Fraunhofer diffraction pattern radiated by the electron bunch, and an image can be reconstructed with the help of a phase retrieval algorithm. This reduces the requirements on the optical hardware by increasing the sophistication in the post-processing of the data collected by the system. Besides, a diffractive imaging setup has the same ultimate resolution of the $4f$ coherent imaging setup.

The applications of coherent OTR imaging are not confined to diagnostics of the transverse distribution of electrons projected along the longitudinal axis. Simple extensions allow for the characterization of the 3D structure of electron bunches with a multi-shot measurement. Such an approach involves a combination of real and reciprocal space imaging spectrometers. Both imaging setups use frequency filters to obtain the spectral data of the image. When the filter bandpass is changed, successive images are recorded at different wavelengths. This process is repeated, wavelength by wavelength. The result is the simultaneous knowledge of two "3D cubes" of spectral data, one in the real space $(\Delta\lambda, \Delta x, \Delta y)$ and the other in the reciprocal space $(\Delta\lambda, \Delta\omega_x, \Delta\omega_y)$, having indicated with $\omega_{x,y}$ the spatial frequencies relative to the x and y axis. Application of the Gerchberg-Saxton algorithm allows one to retrieve the spatio-temporal electron-bunch structure. Also, the determination of the projections of the cube of data in reciprocal space onto specific planes of interest is sufficient to reconstruct the electron-bunch structure, even without knowledge about the cube of spectral data in real space. In other words, the optical replica pulse can be measured in the 3D Fourier domain. We name this novel method Frequency-Resolved Optical Diffractive Imaging (FRODI). FRODI can be further developed from a multi-shot to a single-shot technique to measure the 3D structure of a single electron bunch. This is accomplished by splitting the beam and simultaneously measuring orthogonal (x, t), (y, t) and (x, y) projections. The entire traces can be recorded by three detectors, and used to reconstruct the desired 3D electron-bunch structure. Our 3D imaging technique FRODI turns out to be a relatively simple solution to a very complicated problem, as in our case different spatial frequencies are related to different temporal spectra (i.e. spatial frequency and temporal frequency are coupled).

HOLOGRAPHIC METHODS

Fourier-Transform Holography (FTH) is another promising imaging method. FTH is a non-iterative imaging technique, so the image can be reconstructed in a single step deterministic computation. This is achieved by placing a coherent point source at an appropriate distance from the object and having the object field interfering with the reference wave produced by this point source, detecting the interference pattern in the Fourier plane. For optical applications, the resolution of holographic techniques is not limited by size and quality of the point-like source. It is not difficult to produce a pinhole, unresolved at optical wavelengths, and let sufficiently bright radiation through it. The fast, unambiguous and direct reconstruction achieved in FTH is attractive for coherent OTR imaging of electron bunches. Moreover, FTH may also be used to generate a low-resolution image of the bunch to support diffractive imaging techniques. In this case, multiple references can be added to the FTH setup in order to increase the a-priori information available. Multi-shot and single-shot techniques for the characterization of the electron bunch can also be based on FTH setups, and spatio-temporal FTH techniques can also be used [1]. An extension of the method opens up the possibility for single-shot 3D imaging of ultrashort electron bunches.

Finally, time-gated FTH is another class of possible techniques. A hologram records information about the object only when it is illuminated simultaneously by a coherent reference wave. Then, when a short reference is used, the hologram is equivalent to a time-gated viewing system. We propose a method based on time-gated FTH with multiple reference sources capable of characterizing the spatio-temporal structure of individual electron bunches. Multiple, ultrashort (about 10 fs) reference pulses are generated with a varying time-delay, so that several two-dimensional images (frames) of the electron bunch at different position inside the bunch can be reconstructed from a single holographic pattern. We call this technique Holography Optical Time Resolved Imaging (HOTRI).

REFERENCES

[1] G. Geloni, P. Ilinski, E. Saldin, E. Schneidmiller and M. Yurkov, "Method for the determination of the three-dimensional structure of ultrashort relativistic electron bunches", DESY 09-069, online version at http://arxiv.org/abs/0905.1619