METHOD FOR THE DETERMINATION OF THE THREE-DIMENSIONAL STRUCTURE OF ULTRASHORT RELATIVISTIC ELECTRON BUNCHES

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Abstract

We describe a novel technique to characterize ultrashort electron bunches in X-ray Free-Electron Lasers. Namely, we propose to use coherent Optical Transition Radiation to measure three-dimensional (3D) electron density distributions. Our method relies on the combination of two known diagnostics setups, an Optical Replica Synthesizer (ORS) and an Optical Transition Radiation (OTR) imager. Electron bunches are modulated at optical wavelengths in the ORS setup. When these electron bunches pass through a metal foil target, coherent radiation pulses of tens MW power are generated. It is thereafter possible to exploit advantages of coherent imaging techniques, such as diffractive imaging, Fourier holography and their combinations. The proposed method opens up the possibility of real-time, wavelength-limited, single-shot 3D imaging of an ultrashort electron bunch. **These proceedings are based on the article [1], to which we address the interested reader for further information and references.**

INTRODUCTION

Operational success and optimization of output from XFEL 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 (THOB02).

Elsewhere in these Proceedings we discussed the integration of the ORS setup with a high-resolution electron bunch imager based on coherent Optical Transition Radiation (OTR), Fig. 1. In this paper we further develop this concept to explore the possibility of three-dimensional (3D) ultrashort electron bunch structure characterization with micron-level resolution. 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.

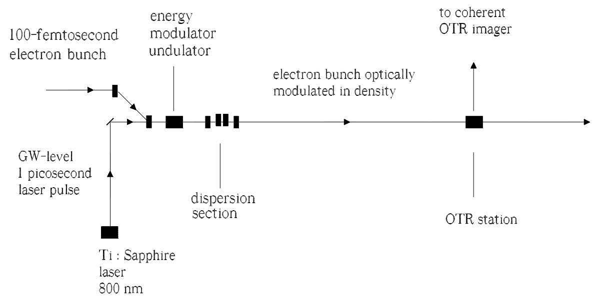

Figure 1: Schematic diagram of the coherent imager. The working principle is based on the optical modulation of the electron bunch and on emission of coherent OTR radiation from the metallic mirror.

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 forma-

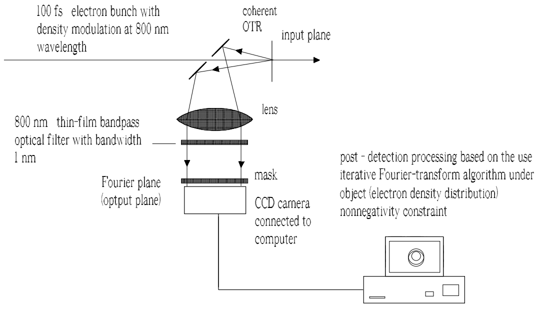

Figure 2: Lens-based setup for diffractive imaging of an electron bunch.

tion 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 AND OTR SOURCE

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. As mentioned in the Introduction, to this purpose we can use the first part of an Optical Replica Synthesizer setup. The integration of the OTR source with the ORS setup is described in detail in [1] and elsewhere in these conference proceedings (WEPC46).

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 (see Fig. 2). This reduces the requirements on the optical hardware by increasing the sophistication in the post-processing of the data collected by the system.

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

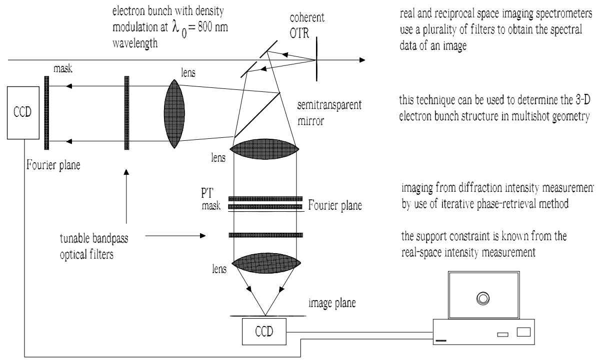

Figure 3: Combination of real and reciprocal space imaging spectrometers for characterizing the 3D electron density distribution by use of multishot measurements.

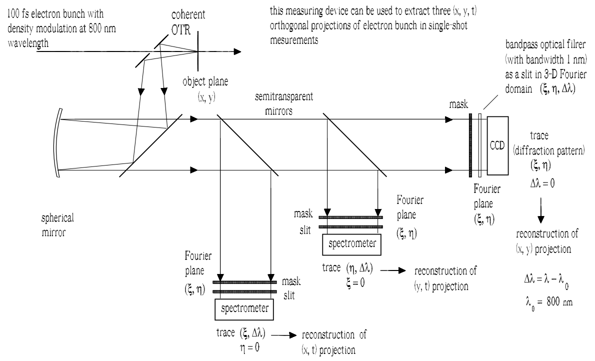

Figure 4: A schematic of FRODI, an apparatus capable of measuring three orthogonal projections of the electron density distribution for a single ultrashort electron bunch. This will allow retrieval of the full 3D structure of the electron bunch.

approach involves, for example, a combination of real and reciprocal space imaging spectrometers (see Fig. 3). 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).

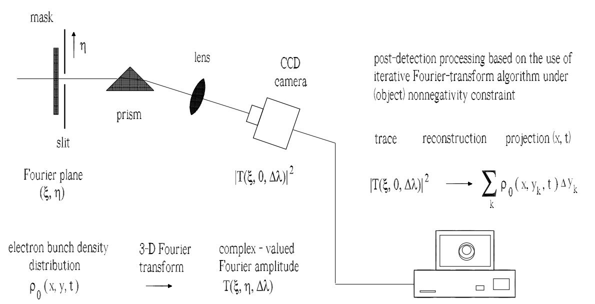

Figure 5: Beam geometry for measurements of the (x,t) electron bunch projection. The prism-lens combination constitutes a spectrometer.

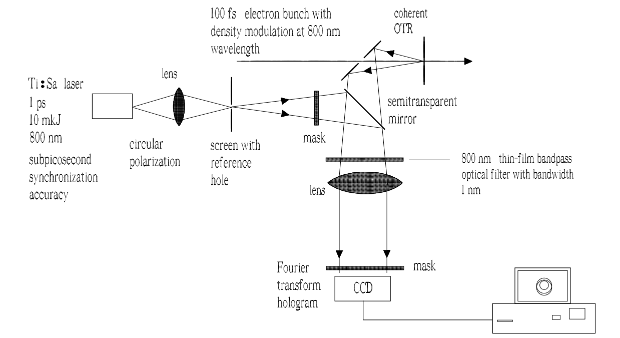

Figure 7: Practical setup for Fourier transform holography using a virtual reference point source.

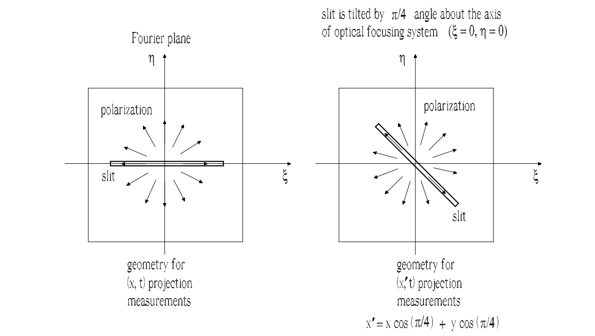

Figure 6: Slit geometry for measuring different projections of the electron bunch with a single-shot 3D imager.

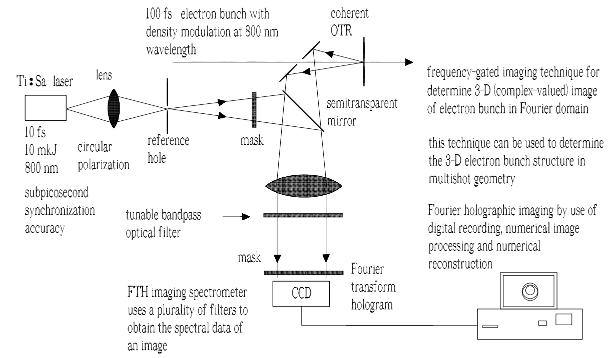

Figure 8: Multishot measurement of the 3D structure of electron bunches by use of frequency-gated Fourier transform holography.

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 (see Fig. 4) by splitting the beam and simultaneously measuring orthogonal (x, t), (y, t) and (x, y) projections (see Fig. 5 and Fig. 6 for the measurement of mixed spatial and temporal frequency components). 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 (see Fig. 7). 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, Fig. 8, and spatio-temporal FTH techniques, Fig. 9, 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 (see Fig. 10 and Fig. 11). 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

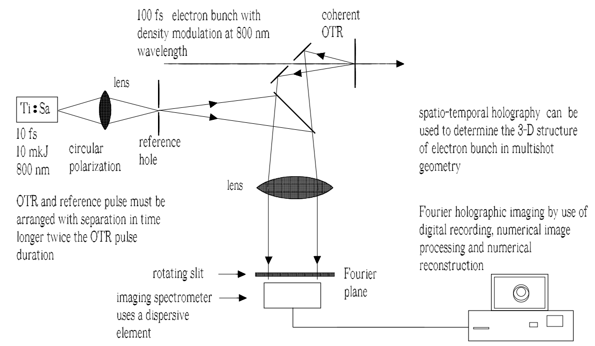

Figure 9: Multishot measurement of the 3D structure of electron bunches by use of spatio-temporal Fourier transform holography.

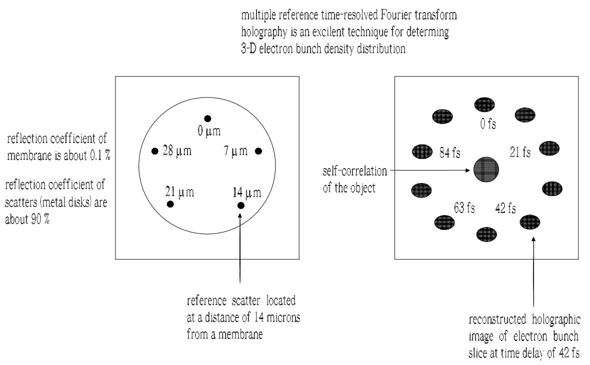

Figure 10: Membrane for time-resolved FTH with reference scatters (left) and reconstructed holographic images of electron bunch slices (right).

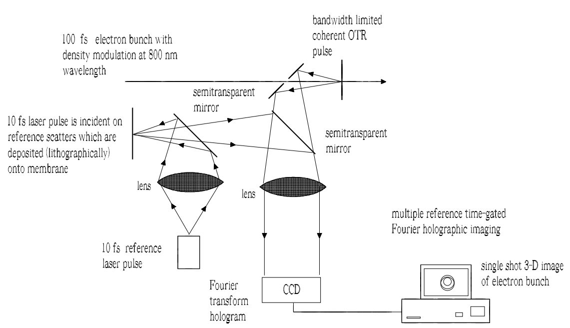

Figure 11: 3D electron bunch structure monitor by use of the HOTRI technique.

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).

As a final note it is worthwhile to mention that, due to the users' needs, future XFELs will operate with shorter and shorter electron bunches. Our proposed diagnostic techniques have the potential for extensions from the 100-fs time scale, which we discussed here, to the 10-fs time scale of electron bunch duration by straightforward rescaling to shorter wavelengths. Exploitation of shorter wavelengths is possible because our setups are based on linear optical elements only. The shortest possible wavelength compatible with glass optics is about 200 nm, which corresponds to the fourth harmonic of a Ti:Sa laser. In fact, using particular geometries, FROG devices can operate in this range as well (see reference [9] in [1]).

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