LONGITUDINAL ELECTRON BEAM DIAGNOSTICS VIA UPCONVERSION OF THZ TO VISIBLE RADIATION

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Abstract

Longitudinal electro-optic electron bunch diagnostics has been successfully applied at several accelerators. The electro-optic effect can be seen as an upconversion of the Coulomb field of the relativistic electron bunch (THz radiation) to the visible spectral range, where a variety of standard diagnostic tools are available. Standard techniques to characterise femtosecond optical laser pulses (auto- and cross-correlators) have led to the schemes that can measure electron bunch profiles with femtosecond resolution. These techniques require, however, well synchronized femtosecond laser pulses, in order to obtain the desired temporal resolution. Currently, we are exploring other electro-optic variants which require less advanced laser systems and will be more amenable to beam based longitudinal feedback applications. The first results of one such new scheme will be presented in this paper.

INTRODUCTION

Single shot electro-optic detection techniques have been successfully applied in electron-beam diagnostics [1, 2, 3, 4]. The longitudinal bunch profile of a single electron bunch can be determined in real-time by detecting its Coulomb field in an electro-optic crystal with a short optical laser pulse. The electro-optic method is not only single-shot and real-time, but also non-destructive and non-intrusive. For example, electro-optic measurements at the soft x-ray free electron laser FLASH show that the SASE process is not influenced by the bunch profile measurements [4, 5].

Several detection techniques exist, but they all have in common that, ultimately, the temporal resolution is limited by the optical probe laser pulse. Currently the highest temporal resolution has been demonstrated at FLASH where electron bunch profiles with at width of 60 fs rms have been observed with a laser pulse of 30 fs (FWHM) [4]. Although these techniques directly provide the temporal profile of the electron bunch, they have several 'disadvantages': (i) the laser pulses have to be very well synchronized with the electron bunches, (ii) the large bandwidth of these ultra-short laser pulses limits the use of many optical components (such as fibers) because of dispersion effects, and (iii) lasers capable of producing ultra-short laser pulses are rather expensive.

In a proof-of-principle experiment, we demonstrate an alternative approach to electro-optic bunch diagnostics with significantly 'less demanding' laser requirements. The schematic of the new technique is shown in figure 1. A (relatively) narrow bandwidth pulsed laser system is used to measure the spectrum of the Coulomb field of a single electron bunch, single-shot and real-time. Here, the result of the electro-optic effect is the generation of sidebands [6] which directly reveal the spectrum of the Coulomb field. It is important to realize that this new detection technique, which measures the *spectrum* of the electron bunch electric field profile, is quite different from the techniques that aim to measure the *temporal profile* of the electron bunch such as electro-optic spectral decoding (EOSD) [1] and temporal decoding (EOTD) [2].

EXPERIMENTAL SETUP

Measurements were performed on relativistic electron bunches that are produced in the linear accelerator (250 pC, 50 MeV) at the FELIX facility [7]. The spectrum of the Coulomb field of a single electron bunch is measured inside the accelerator beam pipe at the exit of the undulator of the FEL (see figure 2). A 0.5 mm thick <110> ZnTe crystal is used as an electro-optic sensor and is placed with

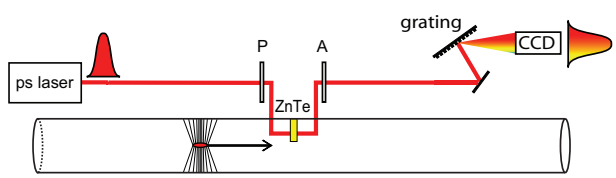

Figure 1: (color) Single-shot technique for measuring the spectrum of electric field profiles of single electron bunches (P and A are polarizers).

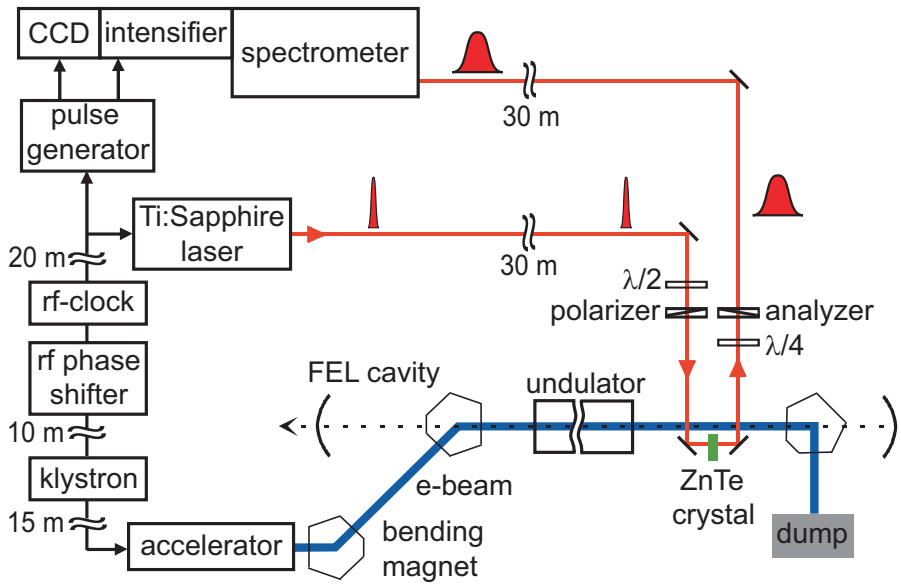

Figure 2: (color) Experimental setup at the FELIX facility. The spectrum of the Coulomb field of a single bunch is measured inside the FEL cavity at the exit of the undulator. The laser system and the spectrometer are located outside the accelerator hall. See text for details.

its front face perpendicular to the propagation direction of the electron beam. The same crystal has been used for measurements in the time domain, using the EOTD technique, showing that the FELIX electron bunches have a width of 275 fs rms [2].

For measurements in the spectral domain, laser pulses with a narrow bandwidth and 'long' pulse duration are required. The laser is a Ti:Sapphire laser with a wavelength of 790 nm producing pulses of 3 ps (FWHM) which is actively synchronized to the accelerator rf clock. The laser is located in a laser laboratory at a distance of 30 m from the accelerator. The laser beam is directed towards electro-optic crystal via mirrors. Before entering the accelerator beam pipe, a half wave plate and polarizer are used to reduce the energy of the laser pulses in order not to damage the electro-optic crystal [5]. In the beam pipe, the pulses are passed through the electro-optic crystal. A quarter-wave plate is used to minimize the residual birefringence of the crystal in the absence of electron bunches. As a result of the electro-optic effect, sidebands are generated by mixing of the frequency components of the bunch electric field and frequency components of the narrow bandwidth probe pulse (the carrier). An analyzing polarizer is used to distinguish the sidebands from the carrier, as they have different polarizations. The spectrum of the sidebands is then measured with a grating spectrometer and an intensified CCD camera which are located in the laser laboratory.

RESULTS

Figure 3 shows a typical measurement with and without the electron bunch present. The measurements were taken using crossed polarizers, which means that the transmittance of the narrow bandwidth probe laser pulse is minimized in the absence of the electron bunch. Nevertheless, there is still some light at the carrier wavelength leaking through the crossed polarizers as can be seen in the figure. In the presence of an electron bunch, the signal broadens due to mixing of the frequency components of the bunch electric field and the laser pulse. The shorter the electron bunch, the broader the spectrum of the electric field of the bunch, and the broader the upconverted spectrum in figure 3.

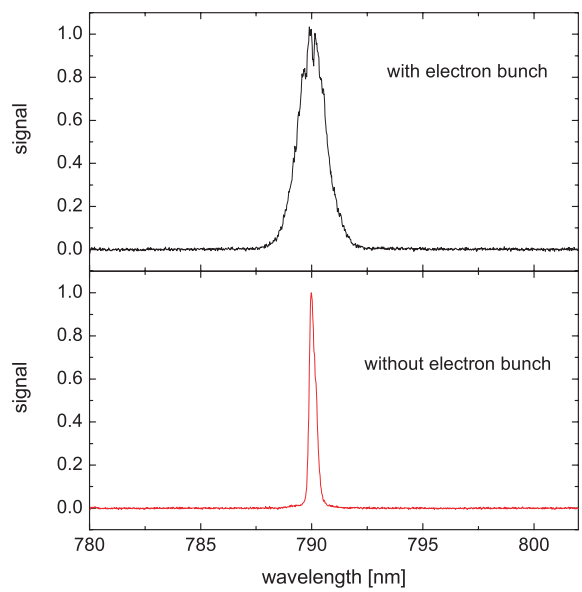

Figure 3: (color) Single-shot spectral measurement with and without an electron bunch.

DISCUSSION

Traditionally, spectral measurements of electron bunches are performed with coherent synchrotron or transition radiation in the far-infrared region. These measurements require far-infrared or THz beamlines to transport the radiation from the electron beam pipe to the spectrometer (for example a Michelson Interferometer). The spectral technique discussed in this contribution circumvents the use of THz beam lines. Here, one needs to deliver relatively narrow bandwidth laser pulses to and from an electro-optic crystal placed adjacent to the electron beam (inside the accelerator beam pipe). This is straightforward and rather easy to achieve, and, although not demonstrated here, allows the use of optical fibers to transport the optical pulses to and away from the accelerator hall.

It should be noted that electro-optic spectral measurements discussed in this paper are different from the temporal measurements using the so-called electro-optic spectral decoding (EOSD) technique. In the EOSD technique, which is described in detail in references [1, 5], a long, linearly chirped probe pulse obtained from a ultra-short broad bandwidth laser pulse is used in a similar setup as shown in figure 1. The electric field profile of the electron bunch is electro-optically encoded onto this chirped probe pulse. In the decoding step, a spectral measurement of the intensity modulated probe pulse directly reveals the temporal profile of the electron bunch.

For the EOSD measurements it is important that the spectral bandwidth of the probe pulse is much larger than the spectral bandwidth of the Coulomb field of the bunch. This is exactly the opposite of the conditions required for the spectral measurements reported in this paper. Here, the spectral bandwidth of the probe pulse should be much smaller than the bandwidth of the Coulomb field. As has been discussed in several papers [2, 5], EOSD is not capable of measuring ultra-short electron bunches, since the temporal profiles of these ultra-short bunches appear broader in the EOSD measurements. This limiting resolution is, in fact, a result of the frequency mixing process which takes place in the EOSD technique as well, and can only be circumvented with the EOTD technique which measures the temporal profile of the electro-optically encoded probe pulse directly [2].

The spectral measurements with a narrow bandwidth laser pulse do not aim to explicitly provide the temporal electron bunch profile. Although compared to EOTD and EOSD, the loss of phase information may seem a backward step, the new measurement technique allows the use of simpler lasers and directly provides a real-time, single-shot spectrum of the electric field. The bandwidth of this technique is determined by the electro-optic mixing effect, and depends on the electro-optic crystal. Frequency components of the bunch electric field up to 4 THz (8 THz) can be converted to optical frequencies with ZnTe (GaP) [8]. The concept can also be extended to high frequency (mid-infrared) spectral components of the bunch profile, through use of different non-linear crystals. The bandwidth is not limited by the beam line for the probe laser, as is the case for THz beam lines in CTR and CSR spectrometers, which allows for measurements of the long wavelength components of the bunch profile.

CONCLUSION

We have demonstrated the measurement of the Coulomb field spectrum of single electron bunches by upconverting it to optical frequencies. This method allows the use of rather simple lasers and directly provides the spectrum of the electric field in real-time and in a single-shot. This longitudinal bunch diagnostic is quite similar to single shot CTR or CSR spectrometers, but avoids the need for special THz beam lines, and allows for the measurement of long wavelength components that cannot be propagated to a remote detector.

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