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Real-time single-shot electron bunch length measurements

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Abstract

Linear accelerators employed as drivers for X-ray free electron lasers (FELs) require relativistic electron bunch with sub-picosecond bunch length. Precise bunch length measurements are important for the tuning and operation of the FELs. Previously, we have demonstrated that electro-optic detection is a powerful technique for sub-picosecond electron bunch length measurements. In those experiments, the measured bunch length was the average of all electron bunches within a macropulse. Here, for the first time, we present the measurement of the length of individual electron bunches using a development of our previous technique. In this experiment, the longitudinal electron bunch shape is encoded electro-optically on to the frequency spectrum of a chirped laser pulse. Subsequently, the laser pulse is dispersed by a grating and the spectrum is imaged with a CCD camera. Single bunch measurements are achieved by using a nanosecond gated camera, and synchronizing the gate with both the electron bunch and the laser pulse repetition rates. The electron bunch length is determined by measuring the laser pulse spectra with and without the presence of an electron bunch. We demonstrate that this method enables a real-time diagnostic for the bunch length of single electron bunches with a time resolution of 370 femtoseconds and a high signal-noise-ratio.

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'The electro-optic detection of the local non-radiative electric field traveling with the electron bunch has recently emerged as a powerful new technique for sub-picosecond electron bunch length measurements [1]. The method makes use of the fact that the local electric field of a highly relativistic electron bunch moving in a straight line is almost entirely concentrated perpendicular to its direction of motion [2]. Consequently, the Pockels effect [3] induced by the electric field of the passing electron bunch can be used to produce birefringence in an electro-optic crystal, e.g. ZnTe, placed in the vicinity of the beam. In our experiment this birefringence is probed by monitoring the change of polarization of the wavelength components of a chirped, synchronized titanium-sapphire laser pulse, similar to the terahertz detection scheme of Zhang et al. [4,5]. When the electric field of an electron bunch and the chirped optical pulse co-propagate in the electro-optic crystal, the polarizations of the various wavelength components of

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the chirped pulse passing through the crystal are rotated different amounts, corresponding to different portions of the local electric field. The direction and degree of rotation is proportional to the amplitude and phase of the electric field. Thus, the time profile of the local electric field of the electron bunch field is linearly encoded on to the wavelength spectrum of the optical probe beam. An analyzer converts the modulation of the polarization of the chirped optical pulse into an amplitude modulation of its spectrum. The time profile of the electric field of the electron bunch is measured as the difference of the spectrum with and without co-propagating electron bunch. The shape of the temporal profile is linear proportional to the longitudinal electron distribution within the electron bunch if the analyzer is not completely crossed with the polarizer and the ZnTe crystal is perfect. The width of the temporal profile corresponds directly to the electron bunch length. Determination of the length and shape of individual electron bunches is achieved by measuring the spectra of single chirped laser pulses with an optical multichannel analyzer equipped with a nanosecond shutter.

Fig. 1 shows the experimental arrangements employed for the single-shot detection of relativistic electron bunches with chirped optical pulses.

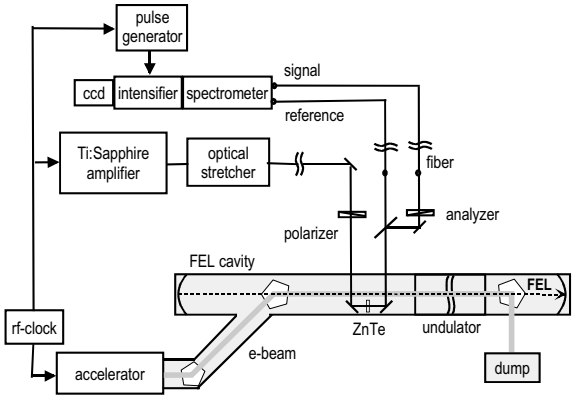

Fig. 1. Experimental arrangements for electron bunch length measurements by electro-optic sampling with chirped optical pulses. The electron bunch length is measured by using an electro-optic crystal of ZnTe placed inside the vacuum pipe at the entrance of the undulator.

The electron bunch source is the radio-frequency linear accelerator at the FELIX free electron laser facility in the Netherlands [6]. The electron beam energy of FELIX was set at 46 MeV, and its charge per bunch at around 200 pC. The micropulse repetition rate is 1 GHz, and the macropulse duration was around 8 μs with a repetition rate of 5 Hz.

Fig. 2(a) shows measurements of the chirped laser pulse spectra with and without a co-propagating electron bunch. The signal spectra are labeled by S and S', the corresponding reference spectra R and R' (Fig. 2(b)). The completely crossed polarizers exhibit a finite transmission of 1.7% if the electron bunch does not overlap with the chirped laser pulse. This is attributed to a small intrinsic stress birefringence of the ZnTe. The transmission of the crossed polarizers changes significantly when the electron bunch and the laser pulse co-propagate: in these circumstances, a large peak, which corresponds to a strong enhancement of the transmission, is observed in the center of the spectrum. The strong change of the spectrum is attributed to the wavelength-dependent change in polarization of the chirped laser pulse due to the electric field of the electron bunch. The length and shape of the electron bunch is obtained by subtracting the spectrum without co-propagating electron bunch, which has been corrected for laser power fluctuations by multiplication by R/R', from the spectrum with co-propagating electron bunch. This difference $S-(S'R/R')$ is corrected for the wavelength dependent variations in intensity in the spectrum by dividing by the spectrum $S'R/R'$. Ideally, if the ZnTe crystal is perfect, i.e. no birefringence, and the polarizers are completely crossed, then the electro-optic signal $S-(S'R/R')$ is proportional to the square of the electric field of the electron bunch. However, since the ZnTe crystal exhibits a small intrinsic birefringence the electro-optic signal is linear proportional to the electric field of the electron bunch [7].

The pixels are converted to time by measuring the length of the chirp τ, the spectral resolution of the spectrometer and CCD setup, $\Delta\lambda$/pixel, and the bandwidth of the chirped laser pulses $\Delta\lambda_{bw}$.

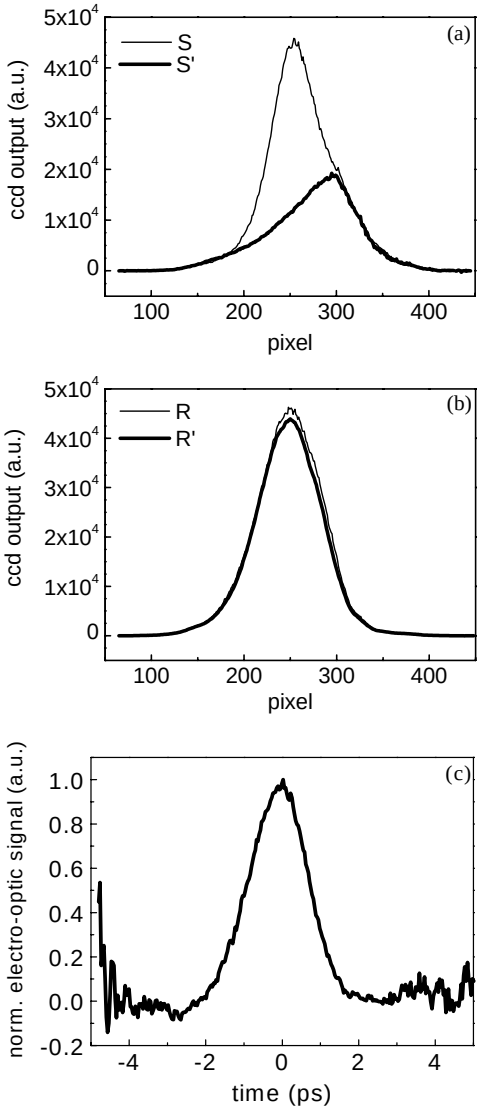

Fig. 2. Single-shot measurements of the electric field of individual electron bunches at the entrance of the undulator inside the vacuum pipe. (a) Raw data, single-shot chirped laser pulse spectra S and S'. The large peak (thin solid line) is detected when the electron bunch and the chirped laser pulse overlap in time. The bold solid line indicates the spectrum that is measured when the laser pulse is 50 ps earlier than the electron bunch. (b) Corresponding single-shot reference spectra R, R'. (c) Electron bunch length and shape obtained from the spectra as displayed in (a). The chirp for this measurement was (4.48 ± 0.23) ps. The electron bunch width is (1.72 ± 0.05) ps (FWHM). The leading edge of the electron bunch is to the right.

Then, the time interval per pixel is given by

$$\frac{\Delta T}{\text{pixel}} = \frac{\Delta\lambda}{\text{pixel}} \frac{\tau}{\Delta\lambda_{\text{bw}}}. \quad (1)$$

In our experiments the parameters were $\Delta\lambda = 0.19$ nm/pixel, $\Delta\lambda_{\text{bw}} = 26$ nm, and the chirp τ was varied between 3 and 20 ps. For the spectra of Fig. 2(a) the chirp was 4.48 ps, which results in an electron bunch measurement as displayed in Fig. 2(c). The width of the electron bunch is (1.72 ± 0.05) ps FWHM. The signal to noise ratio depends on the position in the spectrum. In the center of the spectrum it is better than 200:1. The electron bunch exhibits the expected asymmetric shape [1,8], with the leading edge rising slightly more steeply than the trailing edge. The measured width and shape of a single electron bunch agrees very well with the electron bunch measurements averaged over 8000 electron bunches [1] and CTR measurements [8].

The temporal resolution of the single-shot measurements is determined by the chirp and the bandwidth of the optical laser pulse $\Delta t_{\text{i}} = (\tau_0 \tau)^{1/2}$ [9], the distance R between electron beam and ZnTe crystal $\Delta t_{\text{d}} = 2R/(\gamma c)$ [1], and the resolution of the spectrometer $\Delta t_{\text{s}} = N \times \Delta T/\text{pixel}$. In our measurements, the distance between the ZnTe crystal and the electron beam was 1 mm, $\gamma = 100$, and the resolution of the spectrometer $N = 9$ pixel FWHM. For the measurement displayed in Fig. 2(b), the chirp was $\tau = (4.48 \pm 0.23)$ ps, the unchirped bandwidth-limited laser pulse duration, τ_0, was (31 ± 1) fs, and the time per pixel was (0.033 ± 0.002) ps, so that $\Delta t_{\text{d}} = (70 \pm 10)$ fs, $\Delta t_{\text{s}} = (300 \pm 20)$ fs, and $\Delta t_{\text{i}} = (370 \pm 10)$ fs indicating that the temporal resolution of this measurement is determined by the chirp and bandwidth of the laser pulse. Latest femtosecond laser technology enables the generation of Titanium-Sapphire laser pulses as short as $\tau_0 = 5$ fs [10], so that, with a high-resolution spectrometer and a 1 ps chirp, electron bunch length measurements with an ultimate temporal resolution of ≈ 70 fs are realistically achievable. Note that further improvement is limited by the fact that reducing the distance between the beam and the crystal, so

as to reduce Δt_d, is likely to disturb the electron beam itself.

In conclusion, we have demonstrated electro-optic measurements of the length and shape of individual electron bunches in a 1 GHz electron bunch train. The method allows direct, in-situ electron bunch diagnostics with a high signal-to-noise ratio and sub-picosecond time resolution. The ultimate temporal resolution of the method, and the tunability of the range of linear detection are highly suitable for electron beam diagnostics in next generation linear accelerators and SASE-type FELs.

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