Single-Shot Electron-Beam Bunch Length Measurements

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We report subpicosecond electro-optic measurements of the length of individual relativistic electron bunches. The longitudinal electron-bunch shape is encoded electro-optically on to the spectrum of a chirped laser pulse. The electron-bunch length is determined by analyzing individual laser-pulse spectra obtained with and without the presence of an electron bunch. Since the length of the chirped laser pulse can be easily changed, the electron bunch can be visualized on different time scales. This single-shot imaging technique is a promising method for real-time electron-bunch diagnostics.

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Accelerators employed in new TeV linear electron-positron colliders for high energy physics, or used as drivers for new femtosecond x-ray free electron lasers (FELs), require dense, relativistic electron bunches with bunch lengths shorter than a picosecond. Examples of such new accelerators are the TeV Superconducting Linear Accelerator (TESLA) project at DESY with its integrated self-amplified spontaneous emission (SASE) x-ray FEL [1], and the Next Linear Collider project, or SASE-type Linac Coherent Light Source at SLAC [2]. Precise measurements of the electron-bunch length and its longitudinal charge distribution are necessary to monitor the preservation of the beam quality while the electron-bunch train travels through the beam pipe, as well as to tune and to operate a linear collider or a FEL. For example, at DESY, a 233 MeV electron beam with a full width at half maximum (FWHM) electron-bunch length of 0.8 ps and with 1 nC bunch charge has recently been realized. A further reduction of electron bunch length, down to 130 fs FWHM is planned.

At such accelerators, the electron-bunch train exhibits a characteristic time structure. The train consists of macropulses, with durations typically measured in microseconds, which have a repetition rate of a few hertz. Within a macropulse, the repetition rate of the electron bunches is in the MHz or GHz range. Presently implemented methods of electron-bunch length measurements at accelerators, e.g., interferometric detection of coherent transition radiation (CTR), allow the determination of electron-bunch length as the average over all micropulses within several macropulses [3], but not the measurement of the length and shape of an individual electron bunch within the macropulse. However, the operation of the new accelerators requires extremely high-quality electron bunches. For example, it has been demonstrated that pulse-to-pulse variations of electron beam parameters contribute to unwanted fluctuations of the energy in the SASE-FEL photon radiation pulses [1]. In order to study bunch to bunch fluctuations it is necessary to measure the length of individual electron bunches. The measurement of the length and shape of single electron bunches will allow the investigation of the origin of the electron-beam parameter fluctuations along the bunch train, their correlation with accelerator parameters, and will contribute to an improved performance of the FEL. One strong source of fluctuations of the electron-beam parameters is the interaction of the electron bunches with wake fields in the accelerator cavity [4]. Wake fields are electric fields which are caused by the interaction of the electric field of the electron bunches with the geometry of the resistive wall of the accelerator beam pipe.

Hitherto, in a proof-of-principle experiment, picosecond measurements of the length of individual electron bunches have been demonstrated by a statistical analysis of fluctuations of incoherent photon emissions from the electron bunch [5]. Although this method, in principle, allows subpicosecond electron-bunch length measurements over a wide range of energies, it does not measure the electron-bunch length directly. In order to generate incoherent photon emissions, this method requires the interaction of the electron bunch with an external electric field or medium. Furthermore, the detected frequency of the emission has to be carefully selected in order to avoid coherent emissions and quantum effects. Also, since this method relies on the analysis of photon radiation, it does not allow wake field detection.

In this Letter, we report on the first direct, nondestructive, subpicosecond resolution measurement of the length and shape of individual relativistic electron bunches by electro-optic sampling with chirped optical pulses. Moreover, we demonstrate real-time, single-shot monitoring of the electron-bunch length and shape by means of dynamic

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subtraction of the signals obtained with and without beam. Finally, we show that by shifting the time window of the single-shot measurement, wake fields of individual electron bunches can be measured.

The electro-optic detection of the local nonradiative electric field traveling with the electron bunch has recently emerged as a powerful new technique for subpicosecond electron-bunch length measurements [6]. 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 [7]. Consequently, the Pockels effect [8] induced by the electric field of the passing electron bunch can be used to produce birefringence in an electro-optic crystal 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 Ti-sapphire laser pulse, similar to the terahertz detection scheme of Zhang and co-workers [9]. When the electric field of an electron bunch and the chirped optical pulse copropagate in the electro-optic crystal, the polarizations of the various wavelength components of 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 onto the wavelength spectrum of the optical probe beam. At the frequencies of interest, the phase velocity of the electron field in the crystal and the group velocity of the probe pulse are almost equal, and the same portion of the field is sensed over the length of the crystal. 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 copropagating electron bunch. The width of the temporal profile corresponds directly to the electron-bunch length, and the shape of the temporal profile is proportional to the longitudinal electron distribution within the electron bunch. 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.

Figure 1 shows our experiment setup. The electron-bunch source is the radio-frequency linear accelerator at the FELIX free electron laser facility in the Netherlands [10]. 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 25 MHz, and the macropulse duration was around 8 μs with a repetition rate of 5 Hz. A Ti-sapphire amplifier, producing 30 fs FWHM pulses at 800 nm with a repetition rate of 1 kHz, is used as a probe beam. The 30 fs optical laser pulses are chirped to pulses

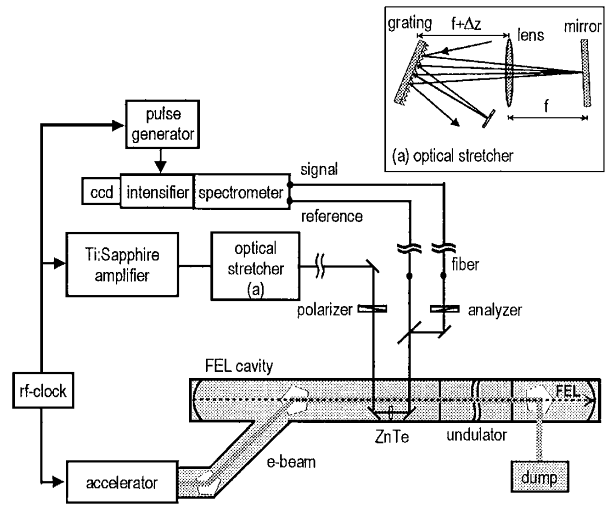

FIG. 1. Experimental setup for electron-bunch length measurements by electro-optic sampling with chirped optical pulses. The electron-bunch length is measured by using a ZnTe crystal placed inside the vacuum pipe at the entrance of the undulator. The inset (a) exhibits a simplified two-dimensional schematic of the optical stretcher. The lens and flat mirror are mounted on a linear translation stage (not shown). The focal length f of the lens is 200 mm.

of up to 20 ps (FWHM) duration with an optical stretcher which consists of a grating, a lens, and a plane mirror [11]. The lens and the mirror act as a telescope with a magnification of -1. In order to obtain a collimated beam and to avoid a spatial chirp, the laser pulses traverse the distance between the grating and the mirror four times. If the grating is placed in the focal plane of the telescope, the optical stretcher produces a zero optical path difference Δz for all wavelength components. If the distance between grating and telescope increases, the optical laser pulses are positively chirped. The duration of the chirped pulses has been measured with an optical autocorrelator based on second harmonic generation in a BBO crystal.

The electron-bunch length is measured inside the accelerator beam pipe at the entrance of the undulator. A 0.5 mm thick $\langle 110 \rangle$ ZnTe crystal is used as an electro-optic sensor and is placed with its 4×4 mm^2 front face perpendicular to the propagation direction of the electron beam. The incoming chirped laser beam is linearly polarized. The outgoing chirped beam is split into a signal beam and a reference beam used to monitor possible laser power fluctuations. The signal beam passes through an analyzer—a second polarizer—which is crossed with respect to the first polarizer. Subsequently, the spectra of the chirped laser pulses are dispersed with a grating spectrometer and the line spectra are focused onto a charge-coupled device (CCD) camera. The CCD camera is equipped with an intensifier, which acts as a nanosecond shutter with a gate width of 100 ns. Single-shot measurements are performed by actively synchronizing the Ti-sapphire amplifier [12] with both the repetition rate of the electron beam and the gate of the CCD camera, and therefore recording only the spectrum of one chirped laser pulse at a time. The temporal overlap between the electron bunch and chirped laser pulse is controlled by an electronic delay.

Figure 2(a) shows measurements of the chirped laser-pulse spectra with and without a copropagating electron bunch. The signal spectra are labeled by S and S'. The 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 copropagate: 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 copropagating electron bunch, which has been corrected for laser power fluctuations by multiplication with the ratio of the reference spectra R/R', from the spectrum with copropagating 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 $S'R/R'$. 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 $\Delta\lambda_{\rm bw}$. Then, the time interval per pixel is given by $(\Delta T/\text{pixel}) = (\Delta\lambda/\text{pixel})/(\tau/\Delta\lambda_{\rm bw})$. In our experiments the parameters were $\Delta\lambda = 0.19$ nm/pixel, $\Delta\lambda_{\rm bw} =$ 26 nm, and the chirp τ was varied between 3 and 20 ps FWHM. For the spectra of Fig. 2(a) the chirp was 4.48 ps FWHM, which results in an electron-bunch measurement as displayed in Fig. 2(b). 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 [6,13], 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 [6] and CTR measurements [13].

The temporal resolution of the single-shot measurements is determined by the chirp and the bandwidth of the laser pulse $\Delta t_i = (\tau_0\tau)^{1/2}$ [9], the distance R between electron beam and the probe beam at the ZnTe crystal $\Delta t_d = 2R/(\gamma c)$ [6], and the resolution of the spectrometer $\Delta t_s = N\Delta T/\text{pixel}$. 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. 2b, the chirp was $\tau = (4.48 \pm 0.23)$ ps FWHM, the unchirped FWHM bandwidth-limited laser pulse duration τ_0 was (31 ± 1) fs, and the time per pixel

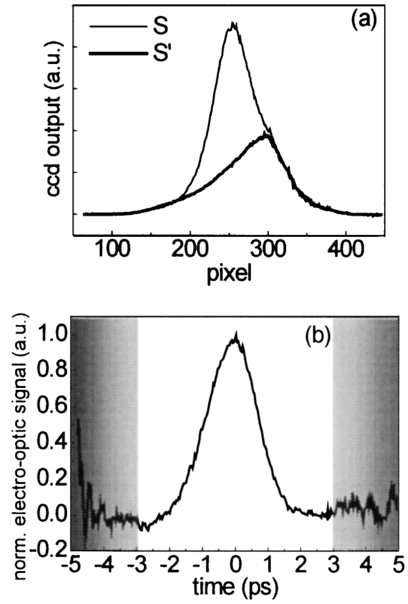

FIG. 2. Single-shot measurements of the electric field of individual electron bunches. (a) Raw data, single-shot chirped laser-pulse spectra S and S'. Spectrum S (thin solid line) is detected when the electron bunch and the chirped laser pulse overlap in time, while spectrum S' (bold solid line) indicates the spectrum that is measured when the laser pulse is 50 ps earlier than the electron bunch. (b) Electron-bunch length and shape obtained from the spectra as displayed in (a). The electron-bunch width is (1.72 ± 0.05) ps (FWHM). The leading edge of the electron bunch is to the right. The shaded areas indicate the regions of increased noise introduced by the correction for the wavelength dependent variations in intensity of the spectrum.

was (0.033 ± 0.002) ps, so that $\Delta t_d = (70 \pm 10)$ fs, $\Delta t_s = (300 \pm 20)$ fs, and $\Delta t_i = (370 \pm 10)$ fs. Although the value of Δt_d is only a rough estimate, these numbers indicate that the temporal resolution of the present measurement was determined by the chirp and bandwidth of the laser pulse. Latest femtosecond laser technology enables the generation of Ti-sapphire laser pulses as short as $\tau_0 = 5$ fs FWHM [14], so that, with a high-resolution spectrometer and a 1 ps chirp, electron bunch length measurements with an ultimate temporal resolution of $\approx$70 fs are realistically achievable. A thinner ZnTe crystal will be needed in that case to reduce the effect of the velocity mismatch and corrections for phonon absorption have to be applied. 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.

The electric field of the electron bunch at the ZnTe crystal was estimated in Ref. [6] to be 7.1×10^6 V/m. The signal-to-noise ratio therefore enables the detection of electric fields as small as 3.5×10^4 V/m. For the detection of the high electric field of electron bunches with charges measured in nanocoulombs (e.g., 3.6×10^8 V/m for a charge of 10 nC), the linear range of electro-optic detection

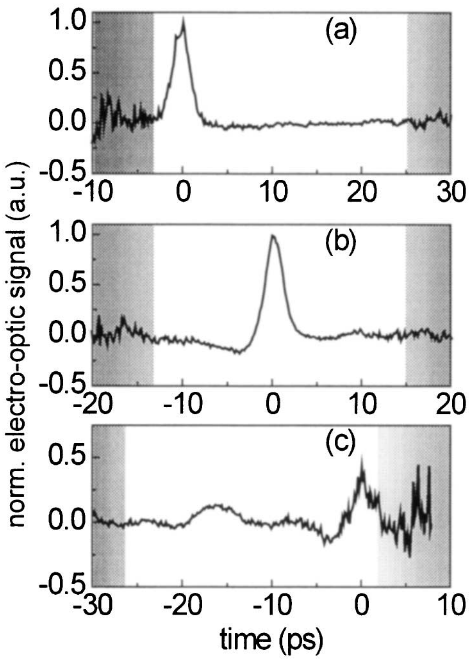

FIG. 3. Single-shot wake field measurements over several tens of picoseconds are performed by choosing a chirp of 18.52 ps FWHM and shifting the synchronized chirped laser pulse with respect to the electron bunch in time. Experimental conditions: (a) Measurements start with electron bunch visible in the time window at 0 ps. (b) The laser pulse has been shifted by 10 ps. Laser pulse and electron bunch now overlap in the center of the time window. (c) Laser pulse shifted again by 10 ps. The signal following the electron bunch is attributed to wake fields excited by the electron bunch in the beam pipe. The shaded areas indicate the regions of increased noise introduced by the correction for the wavelength dependent variations in intensity of the spectrum.

is easily expanded by choosing either a thinner crystal or a material with a lower electro-optic coefficient.

For the tuning of the accelerator during operation, real-time monitoring of the electron-bunch length and shape is highly desirable. In single-shot measurements with chirped optical pulses, real-time monitoring is easily achieved by using a software which continuously performs the dynamic subtraction $(S\text{-}S'R/R')/(S'R/R')$ and displays the result. The time window in which the electron bunch is viewed can be changed as easily as the time scale of an oscilloscope, because the length of the chirped pulse may be altered simply by adjusting the optical path difference Δz in the optical stretcher.

Additionally, we have measured the wake fields of an individual electron bunch. In this measurement (Fig. 3), the laser pulses were chirped to 18.52 ps FWHM, in order to obtain a long observation window. This window was shifted ahead of and behind the synchronized electron bunches. We do not observe a measurable signal when the laser pulse precedes the electron bunch. The electric field of the electron bunch is a large peak when the electron bunch is within the observation window. The signal following the electron bunch, which can be negative as well as positive, is attributed to wake fields. The measurement of the THz spectrum of wake fields is of particular interest because the absorption of the high power THz radiation in the walls of the beam pipe may increase the cryogenic load of superconducting accelerator cavities.

In conclusion, we have demonstrated electro-optic measurements of the length and shape of individual electron bunches in a 25 MHz electron bunch train. The method allows direct, *in situ* electron bunch diagnostics with a high signal-to-noise ratio and subpicosecond 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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