Subpicosecond Electro-optic Measurement of Relativistic Electron Pulses

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Time-resolved measurements of the transverse electric field associated with relativistic electron bunches are presented. Using an ultrafast electro-optic sensor close to the electron beam, the longitudinal profile of the electric field was measured with subpicosecond time resolution and without time-reversal ambiguity. Results are shown for two cases: inside the vacuum beam line in the presence of wake fields, and in air behind a beryllium window, effectively probing the near-field transition radiation. Especially in the latter case, reconstruction of the longitudinal electron bunch shape is straightforward.

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Many applications based on relativistic electron bunches require an accurate measurement of the peak current. For this, the duration and possibly the shape of the electron bunch have to be measured. Free electron lasers (FELs) are important devices that use high peak-current electron bunches and are well-established tunable radiation sources in the (far)-infrared part of the spectrum. Considerable effort has been made, notably at DESY [1] and SLAC [2], to extend the operating wavelength range into the XUV (extreme ultraviolet) and soft x-ray part of the spectrum. Crucial for the success of these projects is the demonstration of self-amplified spontaneous emission (SASE) at short wavelengths. In the SASE mode of operation, an ultrashort, high peak-current, relativistic electron bunch is used to amplify its own spontaneous emission radiation to saturation in one pass through the undulator. Important parameters in these experiments are of course the length and shape of the driving electron bunch, which, together with the total charge in the bunch, yield the current profile. For example, for the DESY project [1], a 25 GeV electron beam with a FWHM bunch length of about 180 fs with 1 nC charge per bunch is planned.

While there are a large number of excellent diagnostics available to measure the shape and duration of ultrashort laser pulses, few measurement techniques exist for short electron pulses. A streak camera system detecting the light pulses generated by the electrons at a target screen was shown to have a limiting resolution of 1.6 ps FWHM [3]. Recently, an off-phase rf-acceleration method has been demonstrated to measure the longitudinal density profile of relativistic electron bunches with subpicosecond time resolution [4], but this approach requires magnetic longitudinal dispersion, an off-phase rf-accelerator section, and an energy spectrometer. In addition, it interferes with normal beam operation and can only measure the beam profile at one particular position in the beam line. Most other diagnostics available to characterize short electron bunches have employed a method that was first described in Refs. [5] and [6]. In this approach the electron beam is passed through a thin foil, and then the electron bunch profile is reconstructed by measuring the spectrum of the coherent part of the emitted transition radiation (usually in the THz-frequency range), and Fourier transforming this to the time domain. The method relies on the use of the Kramers-Kronig relations for the reconstruction process and requires an extrapolation of the measured spectrum to zero frequency. Furthermore, although an asymmetric pulse shape can be obtained, the method cannot distinguish between the leading edge and the trailing edge of the pulse. In this Letter we present measurements based on a completely different approach which avoids these limitations and does not disturb the electron beam. The method is based on the detection of the electric field of the relativistic electron beam when it passes close to a crystal (for example, ZnTe), in which the electric field induces birefringence through the linear electro-optic effect (also known as the Pockels effect) [7], and this birefringence is then probed by a synchronized 12-fs long Ti:sapphire pulse. The induced birefringence causes the initially linearly polarized optical probe beam to become elliptically polarized. The ellipticity can be analyzed by a combination of a quarter wave plate and a Wollaston prism and then measured by a balanced detector [8]. By scanning the delay between the electron pulse train and the Ti:sapphire pulse train the electric field profile, including its sign, is measured (assuming all the pulses are identical). In the relativistic limit, the measured electric field profile is directly proportional to the longitudinal density distribution of the electron bunch.

The Coulomb field of a relativistic electron beam moving in a straight line is concentrated in the direction perpendicular to its trajectory, within an angle of the order of

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$2/\gamma$ [9], where γ is the Lorentz factor. An electro-optic sensor, placed close enough to the beam so that the field of different parts of the electron bunch can be distinguished, is used to sample the Coulomb field of passing electron bunches. The time resolution, τ, when probing the field at a distance of R from the center of the electron beam, can be estimated as $\tau \approx 2R/\gamma c$ (where c is the speed of light in vacuum) [10]. As an example, with $R = 6$ mm and $\gamma = 90$, corresponding to a beam energy of about 46 MeV, one has $\tau = 0.44$ ps, and the resolution clearly improves at higher energies. When the probe pulse and the electron field pulse traverse the sampling crystal at the same speed, the magnitude of the electro-optic effect is proportional to the crystal length. However, in reality, there is a velocity mismatch due to the dispersion in the material, which limits the maximum length at a fixed time resolution. A more important aspect of the dispersion is the response time of the sample's electric polarization. ZnTe has a TO-phonon resonance at 5.3 THz, which means that an electric field pulse shorter than about 200 fs will be distorted and attenuated. It has been shown, however, that frequencies up to 37 THz can still be measured with ZnTe [11], and the effects of the dispersion and absorption can be modeled accurately [12]. An alternative electro-optic sensor material suitable for shorter pulses appears to be GaP, which has its fundamental TO-phonon resonance at 8.7 GHz.

Figure 1 shows the experimental setup used for the electro-optic sampling of the relativistic electron pulses, which are produced by the radio-frequency linear accelerator at the FELIX FEL facility in the Netherlands [13]. Relevant beam parameters are given in Table I. The electron bunch profile is measured at two positions: at the entrance of the undulator [position 1(a)] and behind the exit of the beryllium window [position 1(b)]. A mode-locked Ti:sapphire laser producing a 12-fs pulse at 800 nm with a repetition rate of 100 MHz is employed as a probe beam, and is actively synchronized to the accelerator rf clock [14]. A 0.5 mm thick ⟨110⟩ oriented ZnTe crystal (Ingcrys, U.K.) is used as an electro-optic sensor and is placed perpendicularly to the propagation direction of the electron beam. The polarization direction of the laser probe pulse is set to be parallel to the ⟨001⟩ axis of the ZnTe crystal for optimal electro-optic modulation. The repetition rate of the electron bunch can be changed electronically via a rf-phase shifter which sweeps the electron pulse train over the Ti:sapphire pulse train at a speed of a few picoseconds per microsecond, and the complete electric field profile is thereby measured within a few microseconds. An additional advantage of this rapid scanning technique is that on a time scale of a few microseconds there is a negligibly low jitter of approximately 50 fs between the Ti:sapphire pulse train and the electron pulse train [15].

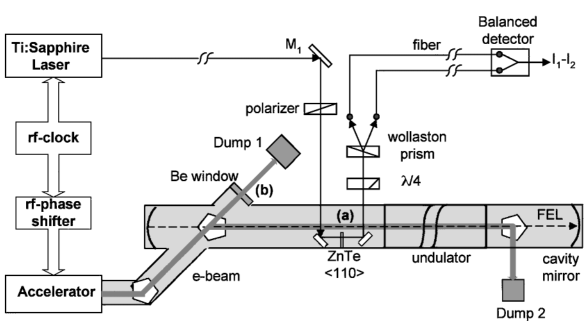

FIG. 1. Experimental setup of the electro-optic measurement of the shape of relativistic electron bunches. The electron bunch profile is measured by using an electro-optic crystal of ZnTe at two positions: (a) at the entrance of the undulator inside the vacuum pipe; (b) in ambient air, between the beryllium window and the current dump (Ti:sapphire beam path and the crystal are not shown). The shaded parts indicate the vacuum housing for the electron beam.

TABLE I. Parameters of the electron beam used for the electro-optic measurements at FELIX.

Beam energy	46 MeV
Energy spread (rms)	0.2%
Normalized emittance	50π mm mrad
Bunch charge	200 pC
Micropulse spacing	1 ns
Macropulse duration	≤8 μs

In the setup in Fig. 1(a), the electric field is measured at the entrance of the undulator inside the vacuum pipe, while the FEL is lasing properly. The electron beam has a diameter of approximately 1 mm at this position and the crystal is located 6 mm from the center of the electron beam. The probe laser pulses propagate in the electron beam direction passing through entrance and exit glass (Kodial) windows, which maintain the polarization state of the probe laser pulse. Figure 2 shows measurements of the observed electric field profile. In the case of Fig. 2(a), the large peak (marked by an arrow) represents the direct field of the electron bunch. It is known that the electron beam at FELIX consists of well-defined bunches of length ~2 ps separated in time by 1 ns. The electric field of the bunch at the crystal will always have the same sign, and the other parts of the signal that have both positive and negative signs are therefore attributed to the wake fields excited by the electron bunches, due to unavoidable discontinuities in the beam pipe [16] and in the measurement system itself. We have also performed measurements with a 40 ns interval between the electron bunches, and in that case there was no measurable signal preceding the main peak. This shows that the oscillations are excited by the passing electron bunch and have not completely disappeared after 1 ns. The ability to measure wake fields *in situ* with high temporal resolution may prove useful in cases where these fields give rise to degradation of the beam quality. The shortest electron bunch we have measured is about 1.7 ± 0.2 ps FWHM, as illustrated in Fig. 2(b), and the rime resolution (estimated as $\tau \approx 2R/\gamma c$ [10]) is about 0.44 ps in this configuration. The electric field strength at the ZnTe

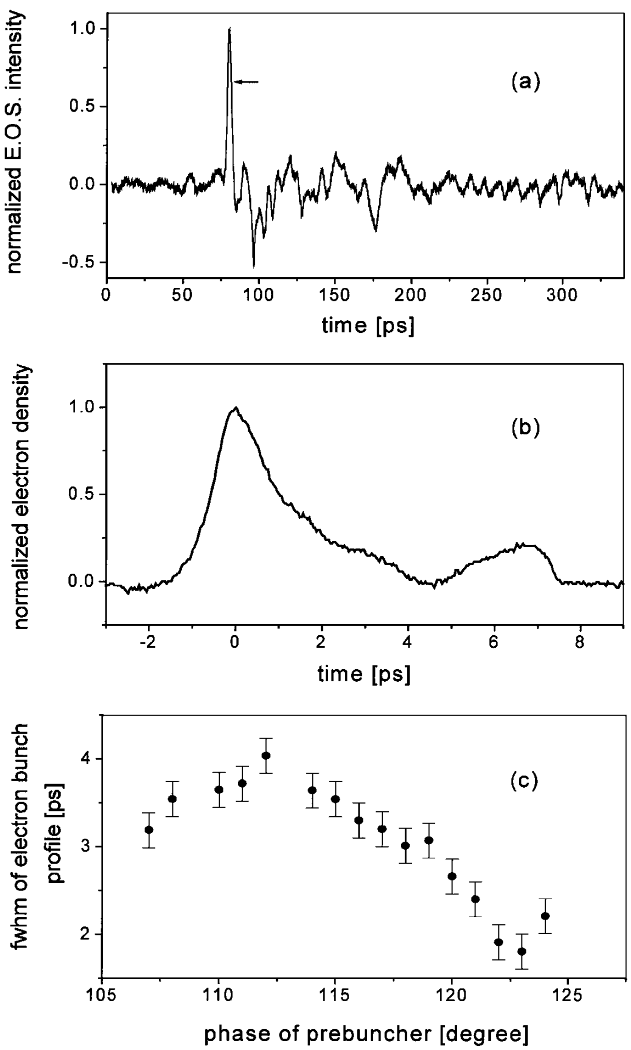

FIG. 2. The electric field profiles measured at the entrance of the undulator inside the vacuum pipe, while the FEL is running properly. (a) Electric field profile measured over several hundred picoseconds, the large positive peak marked by an arrow is the direct field of the passing electron bunch, while the other parts of the signal are attributed to the effects of the wake fields excited by the electron bunches in the beam pipe. (b) The electron bunch profile measured inside the vacuum pipe has a clearly asymmetric pulse shape and the shortest pulse length measured is about 1.7 ± 0.2 ps FWHM. (c) Measured duration of electron bunches as a function of the phase settings of the prebuncher input rf field.

crystal position can be calculated as $E = Q/2\pi\varepsilon_0 R L_b$, where Q is the total charge of the electron bunch and L_b is its effective length [10]. In our case, the electric field strength is approximately 12 kV/cm at the crystal, leading to a sensitivity of our technique of around 1 kV/cm for a $S/N = 1$. The accelerator settings used to drive the FEL at FELIX result in a clearly asymmetric pulse shape. The steep rising edge of the electron bunch is consistent with the observed enhancement of the coherent spontaneous emission, which can considerably facilitate the start-up of a short-pulse FEL at longer wavelengths [17], and is consistent with simulations [18] based on a general particle tracking code [19]. Figure 2(c) illustrates the measured duration of the electron bunches as a function of the phase setting of the prebuncher input rf field. In normal use at FELIX, the prebuncher is used to apply a decelerating field to the leading part of the electron bunch and an accelerating field to the trailing edge of the bunch. It gives a ramp in the energy of electrons with respect to the longitudinal distribution in the bunch. In the drift space between the prebuncher and the buncher, the modulation of the energy of the electron bunch results in a substantial compression of the electron bunch. Indeed, from Fig. 2(c), it can be seen that the electron bunch profile is quite sensitive to the setting of the prebuncher, and the FWHM length may be varied between 1.7 and 4.1 ps.

In a second experiment, the electric field profile is measured at the position shown at Fig. 1(b), where the beam propagates in air after passing through a beryllium window and before being dumped. The beam diameter is about 3 mm at the Be window. The field is probed at a distance of about 6 mm from the center of the electron beam and 120 mm from the Be window. Figure 3 shows the experimental results, where the solid line represents the electric field profile with the accelerator settings normally used for running the FEL, and the dotted line is obtained by slightly adjusting the phase of the prebuncher. From the steep rising edges and the 830 fs FWHM pulse duration of the dotted curve, it is seen that a subpicosecond time resolution can be achieved with this electro-optic sampling technique. Note that at this position, the electron beam is dispersed in the horizontal plane. Therefore, for the dotted line, an energy ramp over the bunch causes the probe laser beam to sample only part of the dispersed bunch,

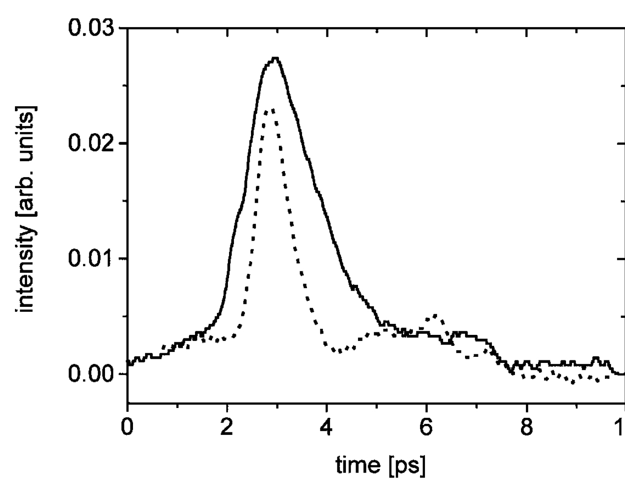

FIG. 3. Near-field profile of the transition radiation generated by the electron bunch at the exit of a beryllium window measured with sub-ps time resolution. Solid line: accelerator settings normally used for running the FEL optimally. Dotted line: phase of the accelerator prebuncher shifted by about 10° at 1 GHz.

leading to a smaller signal and a narrower time profile. In these experiments, there are no surrounding conductive walls, and indeed, no observable wake field effects. In order to minimize the beam spreading after the Be window, the measurement is performed at a relatively short distance of about 120 mm behind the window. At such a distance, the field of the electron bunch has not yet recovered its normal free space configuration at 6 mm from the beam line. Instead of the undisturbed Coulomb field, what is detected can be considered to be the near field of the transition radiation generated by the Be window [20]. However, in the present case, the resulting signal should still give an accurate representation of the longitudinal charge density. The time resolution of our measurement in this configuration is not determined by the spreading of the Coulomb field anymore, but by the finite spot size of the electron beam at the Be window. This finite spot size causes the transition radiation from different parts of the spot to arrive at different times at the sampling crystal. Given the spot size of the electron beam and crystal position, a resolution of 0.5 ps is estimated.

In conclusion, electro-optic measurements of the length and the shape of relativistic electron bunches have been performed with both nonintercepting and intercepting methods. Subpicosecond time resolution can be achieved with the electro-optic detection technique. In addition, it can be used to measure the wake fields inside the beam pipe.

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