Electro-Optic Technique with Improved Time Resolution for Real-Time, Nondestructive, Single-Shot Measurements of Femtosecond Electron Bunch Profiles

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(Received 22 April 2004; published 9 September 2004)

Electro-optic detection of the Coulomb field of a relativistic electron bunch combined with single-shot cross correlation of optical pulses is used to enable single-shot measurements of the shape and length of femtosecond electron bunches. This method overcomes a fundamental time-resolution limit of previous single-shot electro-optic measurements, which arises from the inseparability of time and frequency properties of the probing optical pulse. Using this new technique we have made real-time measurements of a 50 MeV electron bunch, observing the profile of 650 fs FWHM ($\sim$ 275 fs rms) long bunches.

DOI: 10.1103/PhysRevLett.93.114802 PACS numbers: 41.75.Ht, 41.60.Cr, 41.85.Ew, 42.65.Re

Bright electron beam sources producing short, intense, relativistic electron bunches, of the order of 100 fs in duration, are key elements for many new developments in accelerator physics. These sources are essential for future TeV high-energy electron-positron colliders, and as drivers for new femtosecond x-ray free electron lasers (FELs) that are based on self-amplified spontaneous emission (SASE), such as the XFEL project at DESY and the Linac Coherent Light Source at SLAC. Precursors of the two x-ray FELs are the TeV Energy Superconducting Linear Accelerator (TESLA) Test Facility at DESY, where short 250 MeV electron bunches are used for a vacuum ultraviolet FEL operating in the SASE mode [1], and the Sub-Picosecond Pulsed Source at SLAC, which produces ultrashort 28 GeV electron bunches for the generation of short and bright spontaneously emitted x-ray pulses [2].

Another area undergoing significant development is (laser) plasma wakefield acceleration, a process which provides GeV/cm accelerating gradients through collective fields in plasmas [3]. These gradients are orders of magnitude higher than those found in conventional radio-frequency accelerators, which provides a way of constructing very compact accelerators. In order to obtain wakefield acceleration of a monoenergetic electron beam, a sub-100 fs electron bunch needs to be injected at a well defined phase of the plasma wave.

For operating and optimizing these advanced accelerators, electron-bunch length monitors with subpicosecond temporal resolution are essential. Ideally, nondestructive and nonintrusive monitoring of a *single* electron bunch should be available in real time. A promising candidate for such monitors is the determination of the electron bunch longitudinal profile via electro-optic (EO) detection of the copropagating Coulomb field [4,5]. For a highly relativistic electron bunch moving in a straight line in vacuum, the local electric field is almost entirely concentrated perpendicular to its direction of motion. Detection of this field as a function of time at a fixed position therefore provides a way to determine the length and longitudinal shape of the electron bunch. With the EO detection technique, the Coulomb field of the bunch induces birefringence in an EO crystal placed adjacent to the electron beam path. The birefringence is determined through ellipsometry using a synchronized ultrashort laser probe pulse.

Several subpicosecond EO electron-bunch detection schemes have been demonstrated [4–8] and others are proposed [2,7,9]. In the EO "spectral decoding" technique that we previously developed for *single-shot* measurements, the short laser pulse is linearly chirped to a duration exceeding the measurement window. The time profile of the local electric field of the electron bunch is encoded onto the intensity envelope of the chirped optical probe beam and subsequently decoded through a single-shot measurement of the probe spectrum [5].

Recently, the intrinsic time-resolution limitation of the spectral decoding technique has been studied in detail [10,11]. These analyses show that the limitations arising in the decoding process are more restrictive than previously assumed. For ultrashort electron bunches, the result is that the degree of distortion of the measured electric field profile (and thus the temporal resolution of the method) depends on the actual length of the electron bunch, making a rigorous deconvolution of the measured shape impossible. These broadening and distortion effects appear because one obtains the time profile of the bunch electric field from a measurement of the intensity modulated optical spectrum which will contain unwanted spectral sidebands due to the temporal modulation induced by the electric field. A way to circumvent these decoding problems is to measure the intensity modulated pulse in the time domain via a single-shot cross-correlation method where noncollinear second harmonic

generation is employed to produce a mapping of a temporal intensity into a spatial intensity [11].

In this Letter we report EO electron-bunch characterization using temporal decoding performed at the Free Electron Laser for Infrared Experiments (FELIX). We have measured single bunch-generated EO signals with a duration 450 fs FWHM, corresponding to an electric field profile duration of 650 fs FWHM. In another set of experiments, electric field substructure on time scales as short as 460 fs FWHM has clearly been resolved. Furthermore, we compare the temporal resolution of this technique with that of the spectral decoding technique and show that we have overcome the intrinsic time resolution of the latter.

Figure 1 shows our experimental setup. Relativistic electron bunches are produced in the radio-frequency linear accelerator at the FELIX free electron laser facility in the Netherlands. For the measurements described in this Letter, the beam energy was 50 MeV with a maximum bunch charge of 300 pC. The probe laser for the EO measurements is an amplified Ti:sapphire laser (pulse length 30 fs, wavelength 800 nm, pulse energy 1 mJ, repetition rate 1 kHz) that is actively synchronized to the accelerator rf clock [12].

The optical beam is split into two beams of equal intensity. One beam serves as a short-pulse reference beam in the cross correlator; the other beam passes through a grating-pair optical stretcher and is used to probe the birefringence in the electro-optic crystal. The optical pulse is stretched to a length that is longer than the electron bunch: in our case to 21 ps. The stretched pulse passes through a half-wave plate and a linear polarizer and is focused onto a ZnTe electro-optic crystal. This 0.5 mm thick ⟨110⟩ ZnTe crystal is placed inside the accelerator beam pipe at the exit of the undulator.

The input probe polarization is set by the polarizer immediately before entering the beam pipe, and is chosen

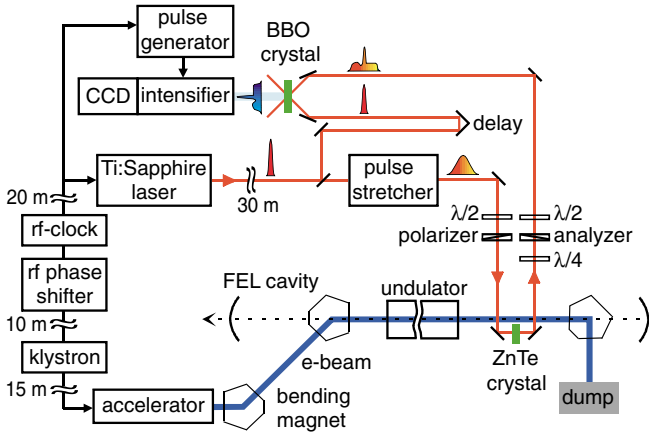

FIG. 1 (color online). Experimental setup for measuring single-shot images of the longitudinal electric field profiles of individual electron bunches.

to maximize the EO retardation for the fixed ZnTe and Coulomb field orientation. The energy of the probe pulse is attenuated to below the ZnTe damage threshold ($\sim 5\ \mu$J) by rotation of the half-wave plate which precedes the input polarizer. On exiting the beam pipe, the probe pulse passes through a quarter-wave plate orientated to remove residual birefringence, followed by an analyzing polarizer set to minimize probe transmission in the absence of any electric field in the crystal. In this way, the phase retardation induced within the ZnTe crystal by the bunch Coulomb field is translated into an intensity modulation on the stretched pulse. In order to retrieve the time information encoded in the probe pulse, a single-shot cross correlation is used in which the intensity modulated chirped pulse and the 30 fs reference pulse are overlapped spatially, but noncollinearly, in a β-barium borate (BBO) second harmonic (SH) generation crystal. The crystal is 0.3 mm thick and the crossing angle between the two Ti:S pulses is 34°. The noncollinear geometry leads to a (transverse) position-dependent time delay between the two Ti:S pulses, which manifests itself in a position-dependent emission of SH (~ 400 nm) radiation. Direct imaging of the SH radiation emitted from the BBO crystal onto a charge-coupled device (CCD) array reproduces the intensity envelope of the chirped pulse.

The solid traces in Figs. 2 and 3(a) show the intensity of the SH radiation generated with a single, but different, synchronized electron bunch (250 pC, 50 MeV), as a function of transverse position on the CCD array. The position is converted into time through knowledge of the beam geometry of the cross correlator, and confirmed by varying the time delay between probe laser and electron bunch. The beam geometry and optical imaging of the SH onto the CCD is chosen to select a 6 ps time window from

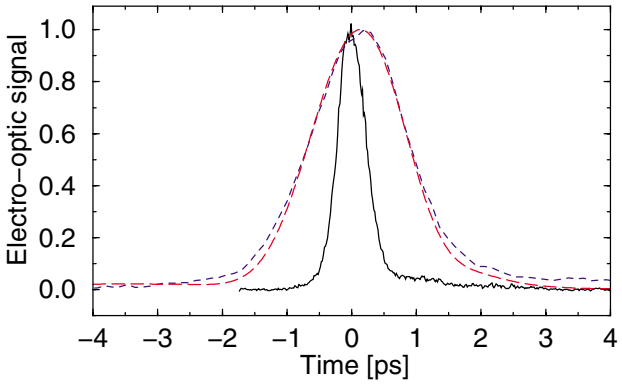

FIG. 2 (color online). Electro-optic detection of the electric field profile of a single electron bunch using the temporal decoding method (solid curve) and the spectral decoding method [short-dashed (blue) line]. The leading edge of the bunch is on the left. The long-dashed (red) curve shows a simulation of the spectral decoding trace obtained by convoluting the temporal decoding trace using Eq. (1).

the 21 ps long probe pulse. For comparison, a spectral decoding measurement, performed under the same experimental conditions by measuring the spectrum of the probe pulse passing through the analyzer, is shown as a dotted curve in Fig. 2.

For the "crossed-polarizer" geometry used here, the signals shown in Figs. 2 and 3(a) do not directly represent the charge density of the electron bunch. From straightforward ellipsometry considerations, the EO signal is expected to scale quadratically with the electric field strength, and hence quadratically with bunch charge. This has been experimentally verified for bunch charges in the range of 140 to 300 pC. The EO signal of a single electron bunch shown in Fig. 3(a) has a FWHM of 450 fs. In Fig. 3(b) the quadratic field dependence has been corrected for, and the corresponding electric field profile that is shown has a 650 fs FWHM (~ 275 fs rms) duration.

The time resolution of EO bunch detection is determined both by the EO encoding process occurring within the ZnTe crystal, and by the spectral or temporal decoding of the optical probe pulse. In our measurements the encoding time resolution is limited by the low Lorentz factor γ of the electrons, and by the response bandwidth of the EO crystal. The increased duration of the Coulomb field at the probe beam position, when compared to the bunch duration, leads to a temporal resolution in the electron-bunch profile of $\Delta t_d = 2R/(\gamma c)$, where R is the radial distance between the electron beam and the optical probe in the EO crystal [5]. At FELIX the maximum beam energy is 50 MeV ($\gamma = 100$) and the distance R is 1.5 mm, thus leading to a temporal resolution of approximately 100 fs. The limitations arising from the EO crystal response are best viewed as a frequency response cutoff, rather than directly as a temporal resolution. For a 0.5 mm ZnTe crystal, electric field Fourier components with a frequency lower than 2.8 THz are detected with minimal distortion, while higher frequency Fourier components are detected with reduced efficiency [13]. A higher frequency cutoff, and hence a better time resolution, can be obtained by using a thinner crystal [13], but at the cost of reduced signal strength, or through the use of alternative EO materials such as GaP. Note that these two time-resolution considerations are valid for other EO detection techniques as well [4,5].

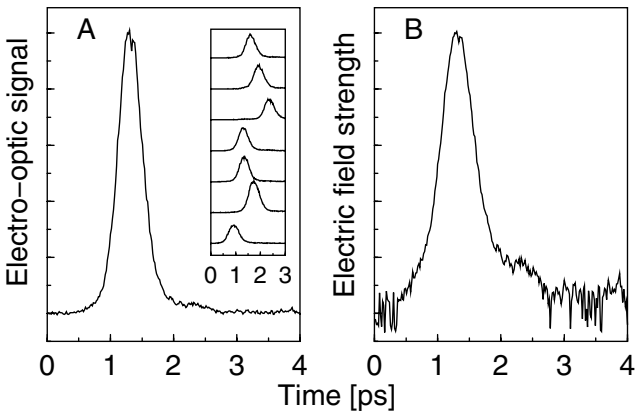

FIG. 3. The electro-optic signal (a) and electric field profile (b) of the same electron bunch. The inset shows a sequence of single-shot measurements, indicating that the timing jitter is of the same order of magnitude as the bunch duration.

In our setup, the imaging resolution of the cross-correlator second harmonic light and CCD camera pixel size are estimated to contribute less than 50 fs to the temporal decoding resolution. Ultimately, the time resolution is determined by the length of the reference optical pulse (30 fs). An analogous single-shot autocorrelation technique routinely characterizes sub-50 fs optical pulses [14]. We are therefore confident that the solid trace shown in Fig. 2 accurately represents the EO intensity modulation of the chirped pulse.

From Fig. 2, it is clear that the spectral decoding introduces significant distortion into the measurements. This distortion arises from the generation of spectral sidebands within the probe pulse. The magnitude of this distortion is a consequence of the long chirped pulse duration of our measurement, and it is natural to consider if using a shorter chirped pulse duration (with a shorter temporal window) is sufficient to retrieve the accuracy of the spectral decoding (SD) measurement, particularly for the characterisation of bunches of 700 fs duration, or shorter. To address the scaling of SD with chirped pulse duration and bunch duration, we consider the approximation of a linearly chirped optical pulse, defined by $\tilde{E}_{\mathrm{opt}}(\omega) = E_0 \exp[i\alpha(\omega - \omega_0)^2 + i(\omega - \omega_0)t_0]$ where α describes the chirp, and with corresponding time varying field $E_{\mathrm{opt}}(t)$. The bunch Coulomb field and the EO effect produce an optical probe pulse (transmitted through the polarization analyzer) according to $E_M(t) = E_{\mathrm{opt}}(t)E_{\mathrm{bunch}}(t)$. From expansion of the Fourier transform of $E_M(t)$ it can be shown that the spectral intensity of the optical modulation will be

$$I_M(\omega) \sim E_0^2 |E_{\mathrm{bunch}}(\tau) * (1 - i)\exp(i\tau^2/4\alpha)|^2, \quad (1)$$

where $\tau \equiv 2\alpha(\omega - \omega_0)$. Figure 2 presents a simulation of the SD measurement, using Eq. (1) with the bunch field $E_{\mathrm{bunch}}(\tau)$ evaluated from the temporal decoding measurement also shown in Fig. 2. Good agreement is obtained with the actual SD measurement. From Eq. (1) it follows that a linear reduction in the bunch duration [$E_{\mathrm{bunch}}(t) \rightarrow E_{\mathrm{bunch}}(at)$] requires a corresponding quadratic reduction in the chirped pulse duration for the same accuracy in the spectral signal to be obtained, i.e., $\alpha \rightarrow \alpha/a^2$.

With our laser bandwidth a <5 ps probe pulse is required to accurately measure a 650 fs bunch duration using SD. The above scaling therefore implies that to accurately measure a 200 fs bunch the probing pulse should be no longer than 500 fs [15]. In the latter case

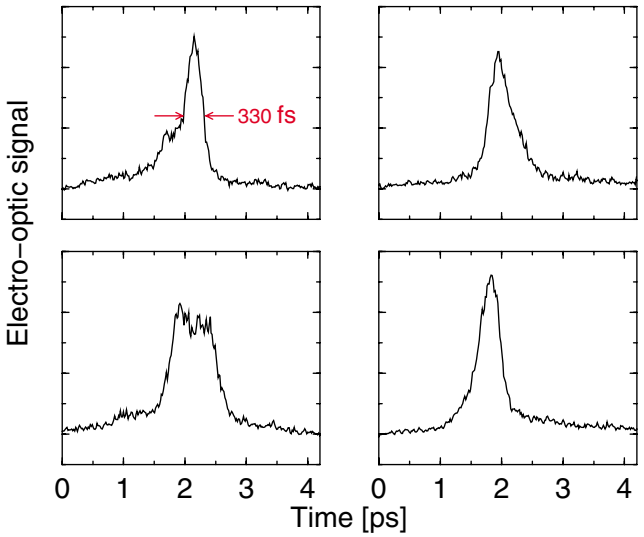

FIG. 4 (color online). Single-shot measurements of individual electron bunches for different settings of the phases of the bunchers and accelerator sections.

the measurement temporal window becomes comparable to the timing jitter, and the usefulness of the technique becomes questionable. In contrast to the SD scaling described above, the temporal resolution of the temporal decoding technique is not only independent of the chirped pulse duration, but, as already mentioned, has a proven sub-50 fs time-resolution capability.

The enhanced temporal resolution of the EO cross-correlation measurements has been used to look at shot-to-shot timing fluctuations between the FELIX electron beam and the actively synchronized Ti:S laser. The inset of Fig. 3 shows a sequence of single-shot measurements recorded at the same settings of the accelerator. From this figure it is clear that the time jitter between the probe laser pulse and the electron bunch is of the order of the width of the electron bunch. At FELIX, the timing jitter originates from both the active locking of the probe laser cavity round-trip time to the rf clock (i.e., synchronization of the laser), and from the jitter of the electron bunches with respect to the rf clock. The latter is mainly determined by phase fluctuations of the klystron feeding the accelerator. For accelerators with a photoinjector, the laser which triggers the photocathode can be used for electro-optic detection of the electron bunches as well, which gives a method to directly monitor the time jitter introduced by bunchers and accelerators. For large accelerator facilities, the electro-optic detection method can produce an accurate trigger for user experiments.

We have also examined the possibility of using the enhanced EO diagnostic for providing real-time information with which to adjust accelerator parameters. Figure 4 shows four electron-bunch measurements obtained at different settings of buncher and/or accelerator phases. Since the results of the measurements were viewed in real time, the consequences of manipulating the settings of the accelerator were immediately known. It is clear that asymmetric bunch shapes can easily be resolved, with no ambiguity in the leading and trailing edges of the bunch profile. Furthermore, this figure provides additional information on the temporal resolution, since the main structure of one of the traces has a FWHM of 330 fs, corresponding to a value of 460 fs for the electric field profile.

In summary, using the temporal decoding technique, we have overcome a fundamental time-resolution limitation of previous single-shot electro-optic measurements, thereby allowing real-time optimization of subpicosecond electron bunches. The combination of electro-optic detection and single-shot cross correlation thus provides a powerful tool for online electron-bunch shape and timing diagnostics for high-brightness electron beams.

We thank Jingling Shen for her many contributions to the development of the single-shot cross-correlation diagnostic and Fred Kiewiet for his helpful suggestions for improving the manuscript. This work is part of the research programme for the FOM, which is supported by NWO, and also the U.K. Research Councils Alpha-X Basic Technology programme.

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