Direct Measurement of the Shape of Short Electron Bunches

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Abstract

We describe a technique to measure the longitudinal density distribution of electron bunches with sub-picosecond resolution by means of electro-optic sampling of the Coulomb field of the electrons.

1. Introduction

Recently, techniques of high-speed electronic measurements have been extended into the THz frequency domain. The availability of ultrashort Ti:Sapphire laser pulses has enabled the measurement of electric fields with sub-picosecond time resolution. This opens up new possibilities for the study of short relativistic electron bunches such as used in free-electron lasers. A direct measurement of the longitudinal shape of the electron bunches now becomes feasible, using methods developed for THz electric field probing.

2. Electro-Optic sampling

In an Electro-Optic (EO) sampling set-up, the field-induced optical activity (Pockels effect) in a sample crystal is measured with an ultra-short probe laser pulse. The change in the polarization state of the probe beam can be detected with high sensitivity, and the response time of the crystal can be very short. Therefore, EO sampling can be used for time resolved probing of both local fields and free-space propagating pulses in the THz range [1].
We intend to apply this technique to the measurement of the Coulomb field of the electron bunches in the FELIX free electron laser. The set-up is sketched in Fig.1. The electron beam passes close to a ZnTe sample crystal, and the EO effect is sensed by a Ti:Sapphire probe pulse traversing the crystal in parallel. A photodiode detects the signal caused by the polarization change.

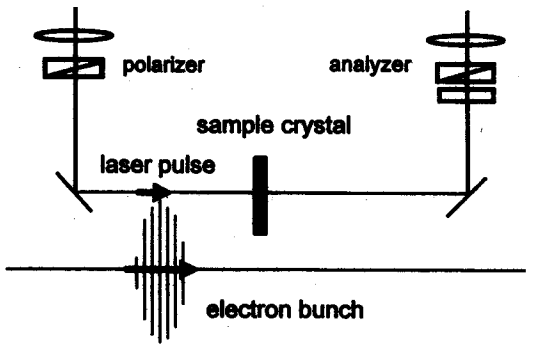

Fig.1 Diagram of the electro-optic sampling set-up

3. Resolution

The Coulomb field of an electron moving at relativistic speed in a straight line is concentrated in the direction perpendicular to its trajectory, within an angle of order $1/\gamma$ [2]. The instantaneous field in a point P at a distance R from a pencil electron beam is mainly determined by the electrons in a range $\pm R/\gamma$ of the bunch length, so that the time resolution obtained by probing the field at P could, ideally, be $\tau \approx 2R/\gamma c$). As an example, for R=10 mm and $\gamma = 100$, $\tau \approx 0.7$ ps; this improves for higher energies. The resolution degrades for a beam with finite transverse emittance, but this is a minor effect when the normalized emittance is smaller than R. When the probe pulse and the THz field pulse traverse the sample with the same speed, the thickness of the crystal adds to the magnitude of the EO effect without reducing the resolution. In reality, there is a velocity mismatch

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due to the dispersion in the material, which limits the useable thickness. An even more important aspect of the dispersion is the response time of the sample's electric polarization. ZnTe, for example, has an LO-phonon resonance at 5.3 THz, which means that field pulses 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 [1] and that the effects of dispersion and absorption can be accurately modeled [3].

4. Sensitivity

The x-component of the electric field at P(R,0,0), caused by an electron with charge q at (0,0,z(t)), moving along the z-axis, is [2]

$$E_x = \frac{2\gamma q}{4\pi\varepsilon_0\left(R^2+\gamma^2 z^2\right)^{3/2}}$$

For a narrow beam of electrons with a longitudinal density distribution $\rho(z)$ varying little over a distance R/γ, the integrated field is

$$E_x = \frac{2\rho(z)}{4\pi\varepsilon_0 R}$$

Taking an average $\rho(z)$ equal to $\rho=Q/l_b$, where Q is the total charge of the bunch and l_b its effective length, we have for the average field produced by the bunch:

$$E_{av} = \frac{2Q}{4\pi\varepsilon_0 R l_b}$$

For example, with Q=200 pC, as in FELIX, R=10 mm, and l_b=1 mm, we have $E_{av} \approx 350$ kV/m. For a probe wavelength of 800 nm and a ZnTe sample of 0.1 mm thick with a Pockels coefficient $r_{14}=4\times10^{-12}$ m/V, this gives a retardation in the order of 4×10^{-3} wavelengths, which should give an easily measurable intensity variation at the detector.
The sensitivity can be considerably improved by a differential detection scheme using a pair of balanced detectors measuring the difference of the signals at orthogonal polarizations [1].

5. Synchronization

In the above, it was tacitly assumed that the probe pulse can reproducibly be made coincident with the field of a given slice of the electron bunch. In practice, synchronization to within the required time resolution is not easily achieved. It has been shown, however, that the jitter between the probe pulses and the output pulses of FELIX can be reduced to 400 fs (rms) through active control of the cavity length of the probe laser [4]. For a better time resolution, the remaining jitter can be overcome by using the differential optical gating (DOG) technique [5].
In principle, it is also possible to perform single-shot measurements, e.g. by using a chirped probe pulse and a spectrometer to separate the signals from different time slices [6]. Alternatively, one could use an intentional velocity mismatch combined with space resolved detection [7]. In these cases, synchronization is not a problem, provided that the sensitivity is high enough to obtain reliable results from a single pulse.

6. Conclusion

Application of the EO sampling technique to the measurement of the Coulomb field of short electron bunches promises to be a valuable method to determine the longitudinal density distribution of the bunches on a subpicosecond timescale. Asymmetric bunch shapes present no special problem, and there is no time reversal ambiguity as in more common methods based on autocorrelation.

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