

REAL-TIME, SINGLE-SHOT TEMPORAL MEASUREMENTS OF SHORT ELECTRON BUNCHES, TERAHERTZ CSR AND FEL RADIATION

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Abstract

Electro-optic detection of the Coulomb field of electron bunches is a promising technique for single-shot measurements of the bunch length and shape in the sub-picosecond time domain. This technique has been applied to the measurement of 50 MeV electron bunches in the FELIX free electron laser, showing the longitudinal profile of single bunches of around 650 fs FWHM [1]. The method is non-destructive and real-time, and therefore ideal for on-line monitoring of the longitudinal shape of single electron bunches. At FELIX we have used it for real-time optimization of sub-picosecond electron bunches. Electro-optic detection has also been used to measure the electric field profiles of far-infrared (or terahertz) radiation generated by the relativistic electrons. We have characterized the far-infrared output of the free electron laser, and more recently, we have measured the temporal profile of terahertz coherent synchrotron radiation (CSR) generated at one of the bending magnets.

ELECTRON BUNCH MEASUREMENTS

At the Free Electron Laser for Infrared eXperiments (FELIX) the longitudinal shape of an electron bunch has been measured via electro-optic (EO) detection of its radial electric field. In this scheme, the electric field induces birefringence in an EO crystal placed in the vicinity of the electron beam. The amount of birefringence depends on the electric field strength and is probed at a single radial position by monitoring the change of polarization of a short optical pulse that is focused to the desired 'observation point'.

In the present FELIX setup, the EO bunch diagnostic is situated at the exit of the undulator of the FEL. A 0.5 mm thick ZnTe crystal is used as an electro-optic sensor and is placed with its front face perpendicular to the propagation direction of the electron beam. The probe laser beam passes through the ZnTe crystal parallel to the electron beam. Figure 1 shows a photograph of vacuum flange containing the EO sensor. The electron beam (50 MeV,

250 pC) passes through the rectangular shaped beam pipe (shape is determined by the undulator). The probe laser beam enters and leaves the vacuum pipe through a side window. On the opposite side of the electron beamline, the EO crystal and two small mirrors are mounted on a translation stage.

Several ways have been demonstrated to measure the electric field induced birefringence in the EO crystal using short optical laser pulses (for an overview see e.g. Ref. [2]). At FELIX, high temporal resolution, single-shot bunch profile measurements have been performed using 'temporal decoding' [1, 3]. The probe laser, which is actively synchronized to the accelerator RF clock, delivers short optical pulses with a duration of 30 fs at a wavelength of 800 nm. Each pulse is split into a probe and a reference pulse. The linearly polarized probe pulse is stretched to a length that is longer than the electron bunch, and is passed through the EO crystal. On exiting the beamline, the electric field induced birefringence is translated into an intensity modulation by passing the probe laser through a



Figure 1: Photograph of the vacuum flange containing the EO sensor. The EO crystal together with two small metal mirrors are mounted on a translation stage (visible on the right). The entrance/exit window for the probe laser beam is visible on the left.

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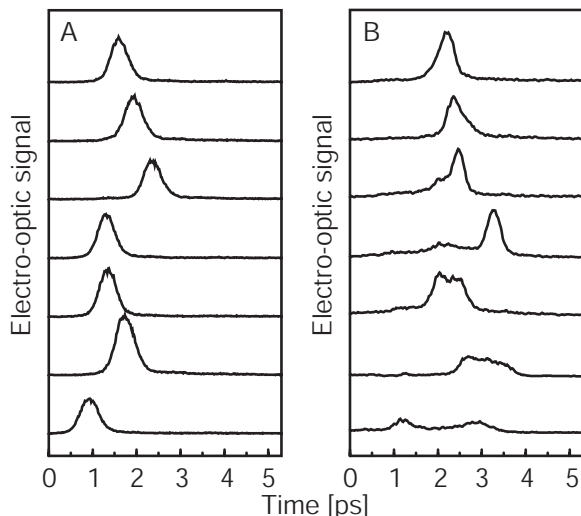


Figure 2: Panel A: a sequence of single shot electron bunch measurements, showing the fluctuations in the arrival time of the bunches. Panel B: single shot measurements of individual electron bunches for different settings of the phases of the buncher and accelerator sections.

polarizer [4]. To measure the ultrafast intensity temporal profile, temporal decoding with a resolution better than 50 fs is performed in a single-shot cross-correlator where the intensity modulated probe pulse is cross correlated with the reference pulse in a BBO crystal. The position dependent emission of the second harmonic light from the BBO crystal is imaged onto an intensified CCD camera.

Examples of single-shot measurements, obtained by binning of the CCD images, are shown Fig. 2. The left panel shows the fluctuations in the arrival time of the electron bunches, illustrating the ability of electro-optic detection techniques to monitor the time jitter introduced by bunchers and accelerators. Furthermore, this method can in principle be used to produce accurate timing information (triggers) for user experiments. Measurements of a sequence of more than 100 bunches shows an rms value of 390 fs for the jitter in the arrival time [5]. Figure 2b shows the dependence of the bunch shape on phase settings of the RF. As data processing is very fast, the diagnostic provides essentially real-time information for optimization of the accelerator settings.

FEL RADIATION MEASUREMENTS

The output from a far-infrared FEL has been characterized with the electro-optic technique using the temporal decoding technique. At a wavelength of $150 \mu\text{m}$, a 20 ps long optical pulse consists of 40 optical cycles and is quasi-monochromatic. Since the timing jitter of the electron bunches (~ 400 fs, see Fig. 2) is of the same order of magnitude as the duration of one cycle of the far-infrared light, it is evident that one needs a single-shot detection technique to resolve the oscillating electric field.

The laser system, the optical stretcher, and the cross-correlator are identical to those used in the electron bunch measurements. For the experiments described in this section, FELIX produces light at a wavelength of $130 \mu\text{m}$ at a macropulse repetition rate of 5 Hz. The micropulse repetition rate is 25 MHz, and the micropulse energy is about $1 \mu\text{J}$. In a FELIX FEL user station, the far-infrared laser beam and the 800 nm probe pulse are spatially and co-linearly overlapped with an ITO coated glass plate acting as a far IR dichroic mirror. A parabolic mirror with a focal length of 100 mm is used to focus the FEL pulse and the probe pulse onto the ZnTe electro-optical crystal. The FEL induced optical retardation is then measured by the combination of polarisers and a single-shot second harmonic generation cross-correlator.

The second harmonic light (400 nm) emerging from the BBO crystal in the cross correlator is imaged onto an intensified CCD camera. The upper panel of Fig. 3 shows an image obtained by subtracting an image without the presence of an FEL pulse (background) from an image where an FEL pulse was present. The image shows a horizontal line because a cylindrical lens had been positioned in the probe pulse path, just before the BBO crystal. In the horizontal direction, the position in the image is proportional to time. The time axis can easily be calibrated since the duration of one cycle (one oscillation of the electric field) is λ/c and the wavelength is known from an online spectrometer. By vertically binning the image, the electric field profile is obtained and is shown in the lower panel of Fig. 3.

The independently determined electric field oscillation period of the FEL pulse measurements makes it attractive to use such FEL pulse measurements for the quantitative

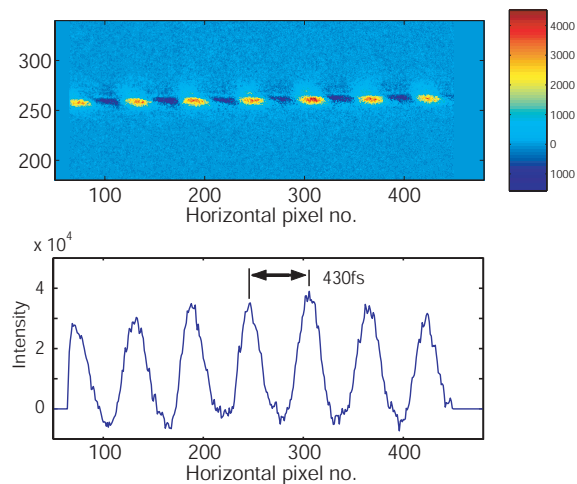


Figure 3: Electro-optic temporal decoding measurement of a quasi-monochromatic FEL pulse. The wavelength is $130 \mu\text{m}$, and one cycle therefore corresponds to 430 fs. The image has been obtained by subtracting an image without the presence of an FEL pulse (background) from an image where an FEL pulse was present. The graph has been obtained by vertically binning the image.

study of the capabilities of EO detection. Furthermore, FEL measurements have been performed outside the accelerator vault, making use of the free access, to pre-align the cross-correlator and imaging setup before undertaking electron bunch measurements.

CSR MEASUREMENTS

At FELIX the THz coherent synchrotron radiation (CSR) emitted from the entrance to a bending magnet has also been measured with electro-optic detection. Bunches with a charge of ~ 200 pC and 45 MeV energy are bent through a 38 cm radius, 45° bend. The CSR radiation is coupled out from the beamline through a crystalline quartz window (see also Fig. 4), collected and focussed onto a ZnTe crystal with a 90° off-axis parabolic mirror. An ITO beam combiner is used to overlap the THz beam and the optical probe beam. The 'spectral decoding' technique [6, 2] is used as the detection scheme. The initial 30 fs probe pulse is linearly chirped to a duration of 20 ps. After passing through a polarizer, the ZnTe crystal, and an analysing polarizer, the probe pulse is coupled into an optical fiber. The other end of the fiber is connected to a spectrometer located outside the accelerator hall. Single-shot spectra of the intensity-modulated probe pulse are measured with a CCD camera.

The spectral decoding signal is obtained by taking the normalized difference between spectra recorded with and without electron bunches present. In Fig. 5, a typical measurement of the electric field profile of the CSR pulse is

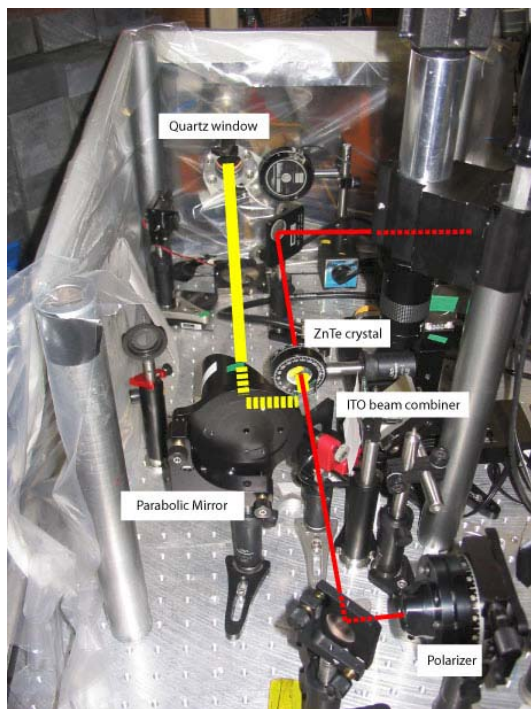


Figure 4: Photograph of the setup for electro-optic detection of CSR pulses.

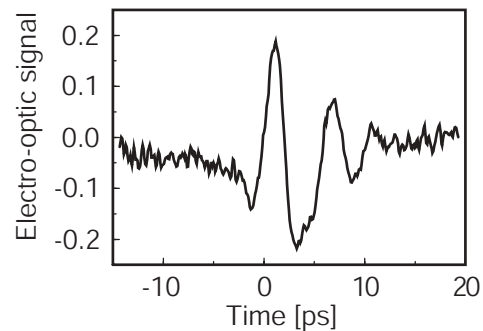


Figure 5: Single-shot electro-optic detection, using the spectral decoding technique, of CSR pulses generated at a bending magnet. Detection takes place outside the vacuum beam line using the setup shown in Fig. 4.

shown. The energy of this THz pulse, measured at the position of the electro-optic crystal, is on the order of 50 nJ.

CONCLUSION

This contribution shows that electro-optic detection can be used for real-time monitoring of the shape and arrival time of electron bunches, far-infrared FEL pulses, and THz CSR pulses. This single-shot method for electron bunch characterization is non-destructive; at FELIX lasing of the FEL can be obtained while monitoring the shape of the electron bunches.

REFERENCES

- [1] G. Berden, S.P. Jamison, A.M. MacLeod, W.A. Gillespie, B. Redlich, and A.F.G. van der Meer, *Phys. Rev. Lett.* **93**, 114802 (2004).
- [2] G. Berden, G.M.H. Knippels, D. Oepts, A.F.G. van der Meer, S.P. Jamison, A.M. MacLeod, W.A. Gillespie, J.L. Shen, and I. Wilke, *Proceedings of the 6th European workshop on beam diagnostics and instrumentation for particle accelerators (DIPAC2003)*, Mainz, Germany, 2003, p. 20.
- [3] G. Berden, B. Redlich, A.F.G. van der Meer, S.P. Jamison, A.M. MacLeod, and W.A. Gillespie, *Proceedings of the ninth European Particle Accelerator Conference (EPAC2004)*, Lucerne, Switzerland, 2004, p. 2697.
- [4] The electro-optic signal scales linearly or quadratically with the electric field depending on the actual settings of the optical components controlling the polarization. For the electron bunch measurements in this paper (Fig. 2) the dependence is quadratic. For the FEL and CSR measurements the dependence is linear, allowing observation of the polarity of the signals.
- [5] G. Berden, B. Redlich, A.F.G. van der Meer, S.P. Jamison, A.M. MacLeod, and W.A. Gillespie, *Proceedings of the 26th International Free Electron Laser Conference, and the 11th FEL Users Workshop (FEL2004)*, Trieste, Italy, 2004, p. 343.
- [6] I. Wilke, A.M. MacLeod, W.A. Gillespie, G. Berden, G.M.H. Knippels, and A.F.G. van der Meer, *Phys. Rev. Lett.* **88**, 124801 (2002)