SPECTRAL DECODING ELECTRO-OPTIC MEASUREMENTS FOR LONGITUDINAL BUNCH DIAGNOSTICS AT THE DESY VUV-FEL

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Abstract

For the operation of a SASE FEL, the longitudinal bunch profile is one of the most critical parameters. At the superconducting linac of the VUV-FEL at DESY, an electro-optic spectral decoding (EOSD) experiment is installed to probe the time structure of the electric field of the bunches to better than 200 fs rms. The field induced birefringence of a ZnTe crystal is detected by TiSa laser pulses that are frequency chirped to ≈ 2 ps. The time structure is encoded on the wavelength spectrum of the chirped TiSa pulse. First results on the bunch length as function of the linac parameters and on time jitter measurements are presented.

INTRODUCTION

Bunch length measurements in the 100 femtosecond regime are of high interest for VUV and X ray free electron lasers. The electro-optical technique provides the possibility to measure the longitudinal charge distribution with very high resolution, determined by the dispersion of the electric field pulse in the nonlinear optical crystal, the frequency bandwidth of the optical laser pulse, and the relative time jitter between electron bunch and laser pulse. At DESY, a titanium-sapphire (Ti:Sa) laser of 50 nm bandwidth is used to determine the birefringence which is induced in a nonlinear electro-optical crystal by the co-moving electric field of a relativistic electron bunch. In the EO crystal, the initial linear polarization of the laser pulse is converted into a slightly elliptical polarization which is then converted into an intensity modulation. Previous accelerator-related EO spectral decoding experiments have been carried out at the infrared free electron laser FELIX [1, 2].

EXPERIMENTAL SETUP

The Ti:Sa laser has a minimum pulse width of 25 fs (FWHM), a central wavelength of 805 nm and a bandwidth of 50 nm. It is mounted on a vibration-damped optical table outside the tunnel. The pulse is stretched by a SF11 prism stretcher, resulting in a linearly chirped pulse of about 2 ps length (FWHM), and then guided into the linac tunnel by a 20 m long optical transfer line equipped with four mirrors and two lenses ($f = 4$ m) which image the Ti:Sa laser onto a 300 μm thick ZnTe crystal in the linac beampipe.

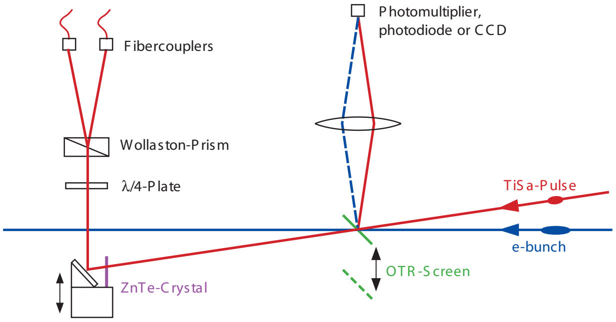

Figure 1: Schematic of the EO setup. An OTR screen can be moved into the e-beam to adjust the relative timing between the laser pulses and the electron bunches with $\approx$ 200 ps precision using a photomultiplier (PMT) or a photodiode.

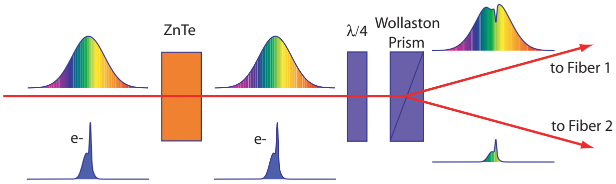

Figure 2: Simplified scheme of the EO spectral decoding. The laser and the field of the bunch are polarized horizontally, parallel to the (-1,1,0) axis of the ZnTe crystal. The Wollaston prism acts as crossed polarizer for the laser beam coupled into fiber 2.

Inside the linac tunnel an optical table is installed which holds the beampipe and the detector optics (see Fig. 1). A spherical mirror ($f = 1$ m) focuses the laser on the ZnTe crystal. The laser beam is injected into the beampipe at an angle of 6° with respect to the e-beam. Thereby we avoid a mirror upstream of the crystal which might produce wakefields. Behind the crystal a mirror reflects the laser beam to the detector optics outside the vacuum chamber. An optical transition radiation (OTR) screen can be moved into the e-beam to adjust the relative timing between the laser pulses and the electron bunches with approx. 200 ps precision before starting an EO measurement.

A simplified view of the signal detection scheme is shown in figure 2. ZnTe is optically isotropic at vanishing field but acquires a birefringence in the presence of a strong electric field. The crystal is cut in the (110) plane with the the crystallographic (-1,1,0) axis oriented horizontally. The electric field of the bunch and the Ti:Sa pulse

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are both polarized horizontally. The induced birefringence can be described by a refractive index ellipse whose large axis is rotated by $45°$ with respect to the horizontal axis. In the crystal, the laser polarization components along the two main axes of the index ellipse acquire a phase shift difference of $\Gamma \propto r_{41}E_e$ where r_{41} is the electro optical coefficient of ZnTe and E_e the electric field of the bunch. Behind the ZnTe crystal the laser pulse will then be elliptically polarized. To measure this ellipticity a Wollaston prism is used as a polarizing beam splitter. The horizontal polarization component is coupled into fiber 1, the vertical (crossed) polarization component into fiber 2 (see figure 2). The quarter wave plate serves the only purpose to compensate the small intrinsic birefringence of the ZnTe crystal. The multimode fibers guide the two polarization components to a spectrometer (SpectraPro 150) located outside the linac tunnel. The image of the spectrum is recorded with a gated intensified camera (Andor DH720-18F). Single shot spectra of individual bunches can be taken with a repetition rate of up to 60 Hz. In the case of temporal overlap between the laser pulse and the electron bunch, the temporal profile of the electron bunch is encoded on the spectrum of the laser pulse from fiber 2, while the spectrum from fiber 1 can be used for normalization. Without temporal overlap no signal is transmitted into fiber 2.

TEMPORAL RESOLUTION

The time resolution of the EOSD method is determined by [3]:

- the material and thickness of the electro-optical crystal. The lower limit for a 300 μm thick ZnTe crystal was calculated to be approx. 250 fs (FWHM) [4].
- the bandwidth-limited length of the laser pulse $\tau_0 = 25$ fs and the length $\tau_c = 2$ ps to which it is stretched. For bunch lengths shorter than $(\tau_0\tau_c)^{1/2} \approx 245$ fs (FWHM) the measured profile will be broadened and/or distorted [5].
- the distance $r = 12$ mm from the electron beam to the EO crystal, $\Delta t_d \approx 2r/\gamma_c \approx 90$ fs (rms) [6].
- the resolution of the spectrometer and camera which contributes about 40 fs.

The resulting total resolution is 400 fs (FWHM) or 175 fs (rms), which is approximately the same as the shortest peaks seen in the measurements presented here. Measurements with increased resolution using a thinner crystal and a laser with larger bandwidth are currently prepared.

The arrival time of the bunch at the EO crystal can in principle be measured to better than one quarter of the resolution ($>$ 50 fs), additionally the time jitter of the synchronization between the laser and the 1.3 GHz linac master oscillator of approx. 70 fs (rms) has to be taken into account [7].

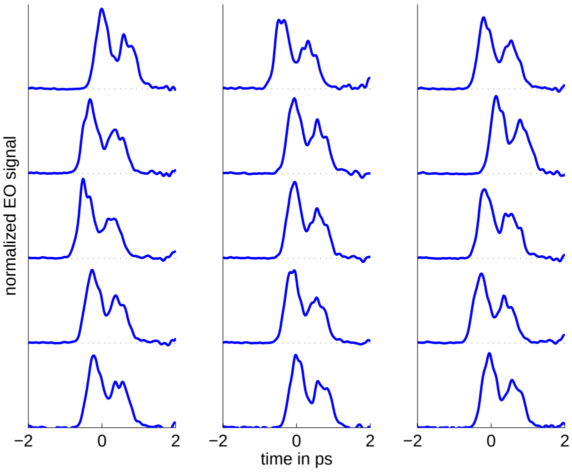

Figure 3: Single shot measurements of 15 consecutive bunches. The leading edge of the bunch is on the left.

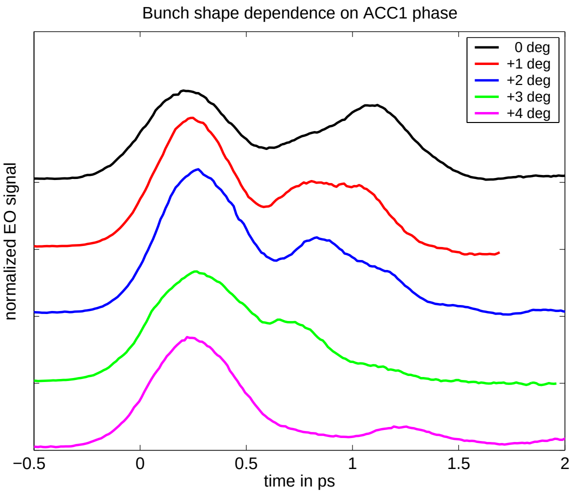

Figure 4: Measurement of the bunch field for different settings of the phase in the first accelerating module. Each line represents the average of 100 normalized and time jitter corrected single shot measurements. The leading edge of the bunch is on the left.

MEASUREMENTS

Figure 3 shows single-shot measurements of 15 consecutive bunches. One observes longitudinal field distributions of approx. 1 ps length containing of two peaks that are $\approx$ 700 fs apart and 160 fs to 250 fs wide (rms). These data are in qualitative agreement with measurements using a vertically deflecting cavity, where similar bunch shapes were found at the same accelerator settings [8]. Changing the rf phase in the first accelerating module by $4°$, the bunch could be compressed to a single peak (Fig. 4).

Figure 5 show averaged single-shot measurements for different bunch charges. An almost linear dependence of the signal amplitude on the bunch charge is observed with slight changes in the signal shape, probably due to different

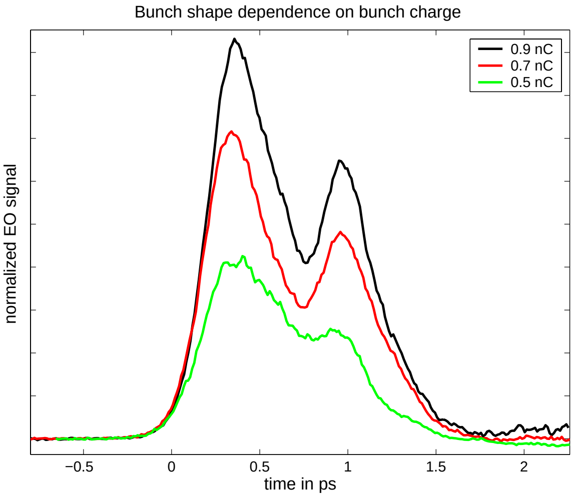

Figure 5: Measurement of the bunch field for different bunch charges. Each curve represents the average of 600 normalized and time-jitter corrected single-shot measurements. The leading edge of the bunch is on the left.

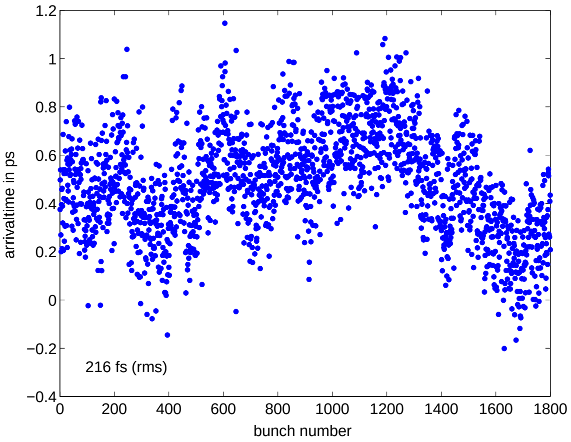

Figure 6: Arrival time of the electron bunches at the ZnTe crystal, measured with respect to the 1.3 GHz reference frequency. The rms time jitter is 216 fs.

space charge effects during the acceleration of the bunch.

For a series of measurements the arrival time of the bunches at the EO crystal, relative to the 1.3 GHz reference frequency, was determined by fitting a Gaussian to the first peak of the signal. The data in figure 6 cover a time interval of 15 minutes at a bunch repetition frequency of 2 Hz. The rms time jitter is 216 fs, including the above mentioned 70 fs time jitter of the synchronization between the laser and the 1.3 GHz linac master oscillator. Measurements ranging from 2 to 30 minutes show rms time jitters between 140 fs and 1 ps, including slow time drifts.

CONCLUSION

The Electro-Optical Spectral Decoding technique offers the opportunity of an online non-destructive single-shot measurement of the longitudinal bunch shape with a resolution of better than 175 fs, and simultaneous timing measurements with a resolution of better than 50 fs.

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