ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-WEOA03

FIRST ELECTRO-OPTICAL BUNCH LENGTH MEASUREMENTS AT THE EUROPEAN XFEL

B. Steffen*, M.K. Czwalinna, Ch. Gerth, P. Peier†,
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Abstract

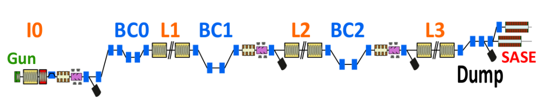
Three electro-optical bunch length detection systems based on spectral decoding have been installed and are being commissioned at the European XFEL. The systems are capable of recording individual longitudinal bunch profiles with sub-picosecond resolution at a bunch repetition rate 1.13 MHz. Bunch lengths and arrival times of entire bunch trains with single-bunch resolution have been measured as well as jitter and drifts for consecutive bunch trains. In this paper, we present first measurement results for the electro-optical detection system located after the second bunch compressor. A preliminary comparison with data from the bunch arrival-time monitor shows good agreement.

INTRODUCTION

The accelerator for the European X-ray Free-Electron Laser (E-XFEL) delivers femtosecond electron bunches at an energy of up to 17 GeV at a repetition rate of up to 4.5 MHz in bursts of up to 2700 bunches every 100 ms. The electron bunches can be distributed between three undulator beamlines, and the generated femtosecond X-ray laser pulses at wavelengths between 0.05 nm and 6 nm can serve up to three user experiments in parallel [1].

Short electron bunches with a high peak current are needed to drive the SASE process in the magnetic undulators. To reach these short bunches, the initially long electron bunches created at the photocathode gun are compressed in three magnetic bunch compressor chicanes BC0, BC1 and BC2 downstream of the respective accelerating sections I0, L1 and L2 (see Table 1).

Table 1: Design electron bunch lengths (rms) for different operation modes [2].



	130 MeV	700 MeV	2.4 GeV	17.5 GeV
20 pC	4.5 ps	1.5 ps	190 fs	5 fs
100 pC	4.8 ps	1.6 ps	200 fs	12 fs
250 pC	5.3 ps	1.7 ps	220 fs	25 fs
500 pC	6.0 ps	2.0 ps	260 fs	43 fs
1 nC	6.8 ps	2.2 ps	300 fs	84 fs

Various diagnostic devices have been installed along the accelerator to measure the longitudinal properties of the electron bunches. Transverse deflecting structures (TDS) have been installed in the injector [3] and downstream of BC2 at final bunch compression for the measurement of slice emittance, longitudinal phase space and longitudinal bunch profile. These properties can be measured for single electron bunches with high accuracy, since the electron bunches are streaked and imaged onto a screen. However, as a consequence, the bunch properties are degraded and these bunches are not delivered to the undulators but deflected by fast kicker magnets out of the bunch train into a dump upstream of the undulators .

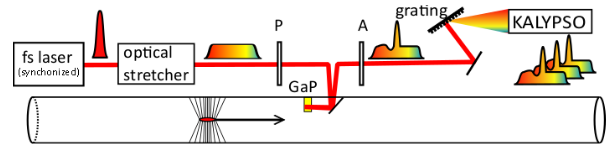


Figure 1: Schematic drawing of a spectrally encoded electro-optical detection setup. P: polarizer; A: analyzer (quarter-wave plate, half-wave plate, polarizer).

Electro-optical bunch length detection (EOD) [4] offers the possibility of measuring the longitudinal bunch profile and arrival time in a non-destructive manner with single bunch resolution for every bunch in the bunch train. Three EOD systems have been installed: One downstream of the injector linac I0 at 130 MeV, one downstream of BC0 (and L1) and one downstream of BC1 at a beam energy of 700 MeV. An EOD system was not foreseen downstream of BC2 due to the limited time resolution.

Bunch arrival time monitors (BAM) [5] have been installed downstream of the injector linac and after each of the bunch compressors BC0, BC1 and BC2. The BAMs measure the arrival time of individual electron bunches with femtosecond precision relative to an optical reference system and can be used for a feedback on the RF of the accelerating modules to stabilize the arrival time which is critical in pump-probe user experiments.

ELECTRO-OPTICAL BUNCH LENGTH DETECTION

Electro-optically active crystals like gallium phosphide (GaP) become birefringent in the presence of an electric field. The electro-optical detection techniques use this effect to transfer the temporal profile of fast changing electric fields by sampling the change in birefringence with laser pulses. Afterwards, the modulated temporal profile of the laser pulse can be analyzed with classical laser techniques.

Several different electro-optical detection techniques have been established for single-shot bunch length measurements at different electron accelerators in the past decade, among them:

* bernd.steffen@desy.de
† now at METAS, Bern, Switzerland

ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-WEOA03

Spectrally resolved electro-optical detection (EOSD): It uses a chirped laser pulse, where the frequency components of a broadband laser pulse are sorted in time and the temporal profile can be retrieved from its modulated spectrum using the known relationship between wavelength and longitudinal (temporal) position in laser pulse [6] (see Fig. 1).

Spatially resolved electro-optical detection: A short laser pulse passes through the EO crystal at an angle, mapping the temporal profile of the field pulse in the transverse profile of the laser pulse due to its different arrival times at different positions of the crystal surface [7].

Temporally resolved electro-optical detection: The temporal profile of the modulated laser pulse is measured in a single-shot cross-correlation with another short laser pulse [8].

The maximum rate of all systems is limited by both the repetition rates of the laser system and line detector. Temporally and spatially resolved detection offer a high time resolution as good as 60 fs, but they have higher demands on the imaging system for the laser and need higher laser pulse energies compared to EOSD.

With the EOSD it has been shown that sub-ps electron bunches of about 100 pC charge can be measured with about 200 fs resolution using the Coulomb field of the relativistic electron bunch [4, 9]. For a more comprehensive description of electro-optical detection techniques and theory see [9, 10].

Since the E-XFEL is build in a single-tunnel design, the laser and all electronics have to be placed in radiation shielded racks underneath the electron beam line. The EODS scheme was chosen for the E-XFEL to design a compact, fully remote-controlled and reliable system, meeting the requirements for bunch length measurements up to the entrance of bunch compressor BC2.

EOD SYSTEM AT THE E-XFEL

The EOD system consists of six sub-systems:

- Ytterbium fiber laser and amplifier,
- Optics set-up at the beam line vacuum chamber incl. the GaP crystal,
- Spectrometer with the KALYPSO MHz line detector,
- MicroTCA.4 crate with the analogue and digital boards for laser synchronization and data readout,
- Laser to RF synchronization unit with other supporting electronics,
- Driver unit for the motors in the laser and at the beam line.

All but the optics set-up are placed in the radiation shielded 19 " rack underneath the electron beam line with a total of 25 height units.

The laser consists of an Ytterbium fiber oscillator (adapted from the design developed at the Paul-Scherrer-Institute [11]) with a repetition rate of 54.167 MHz which is synchronized to the radio-frequency (RF) master oscillator of the E-XFEL timing system [12]. Before the fiber amplifier the repetition rate is reduced by an acusto-optical modulator based pulse

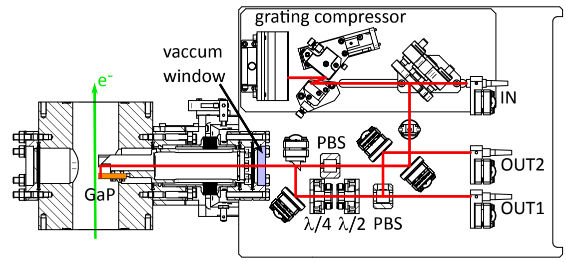


Figure 2: Assembly drawing of the optics set-up at the electron beam line including the vacuum chamber (left). PBS: polarizing beam splitter.

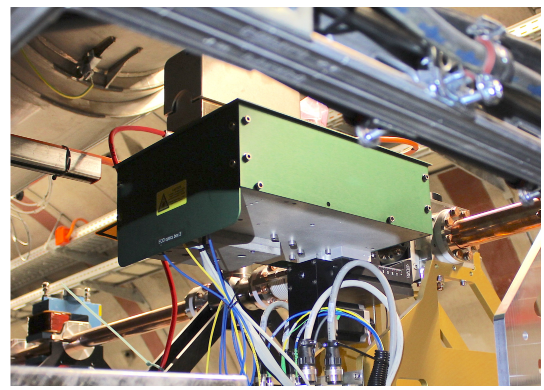


Figure 3: Picture of the optics set-up and vacuum chamber at the electron beam line.

picker to ms long bursts at 10 Hz with a pulse spacing of 886 ns (1.13 MHz E-XFEL operation frequency).

The resulting laser pulses with a bandwidth of about 100 nm, a central wavelength of 1050 nm and a pulse energy of 20 nJ-100 nJ are led by a 10 m long polarization maintaining optical fiber to the optics set-up at the vacuum chamber in the accelerator beam line.

This set-up is adapted from the design for the SwissFEL [13], but additionally equipped with a grating compressor to adjust the length and chirp of the incoming laser pulse from full compression to about 5 ps (FWHM). The GaP crystal and the downstream mirror are mounted on a holder which is mounted on a motorized vacuum feed-trough (see Figs. 2 and 3). The set-up in the injector is equipped with a 5 mm-thick GaP crystal whereas both systems downstream of BC0 and BC1 are equipped with 2 mm-thick GaP crystals to match the bunch lengths to be measured. Outside the vacuum a small breadboard is fixed to the feed-through which holds the required optics including the fiber couplers. This way all optical elements from the fiber coming from the laser to the fiber going to the spectrometer, including the EO crystal are rigidly coupled, avoiding any misalignment or timing changes when the crystal is moved closer to the electron beam or withdrawn from the beam-pipe [13].

The output pulse is then send via an optical fiber to a simple grating spectrometer with approx. 1 nm resolution. It is equipped with an InGaAs-KALYPSO (KArlsruhe Linear arraY detector for MHz rePetition rate SpectrOscopy) [14]

ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-WEOA03

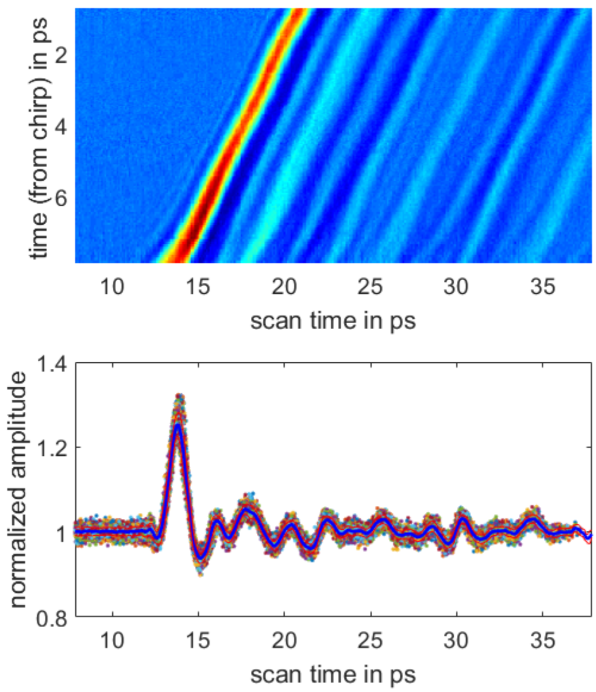


Figure 4: Top: 2D plot of single-shot EOD traces (vertical) taken at different laser timings (horizontal). Bottom: Stacked EOD traces from the scan above. The blue line shows the average, the red lines the standard deviation.

line detector, which can deliver singe shot spectra with 256 pixels and a repetition rate of up to 2.26 MHz to the High-speed Optical Line Detector readout FPGA mezzanine card (HOLD) [15]. The data is transferred via a high-speed optical data link to the MicroTCA.4 [16, 17] crate, which also carries the analogue and digital boards for laser synchronization, timing and triggers and provides the link to the accelerator control system.

MEASUREMENTS

All measurements presented in this paper have been performed during commissioning of the SASE1 undulator and photon beam lines. The data was taken at the EOD station downstream of BC1 at a electron beam energy of 700 MeV, a bunch charge of approx. 500 pC and SASE pulse energies of 500 µJ and 800 µJ for the first data-set (Figs. 4 and 5) and second data-set (Figs. 6 and 7), respectively.

For a given laser chirp, defined by the initial chirp of the pulses from the laser system and the setting of the grating compressor at the beam line, a time calibration can be done by scanning the laser pulse over the electron bunch at stable accelerator conditions. The laser synchronization allows sub-picosecond time steps with high accuracy and the resulting shift of the bunch signal in the laser spectrum allows a detector pixel to time calibration.

The result of a calibration is shown in Fig. 4 (top), where each vertical line represents an average of five single-shot EOD traces taken at the laser timing given at the horizontal axis. Shifting each trace by the known laser time shift, the traces can be stacked to give a averages signal over the full time window scanned (Fig. 4, bottom).

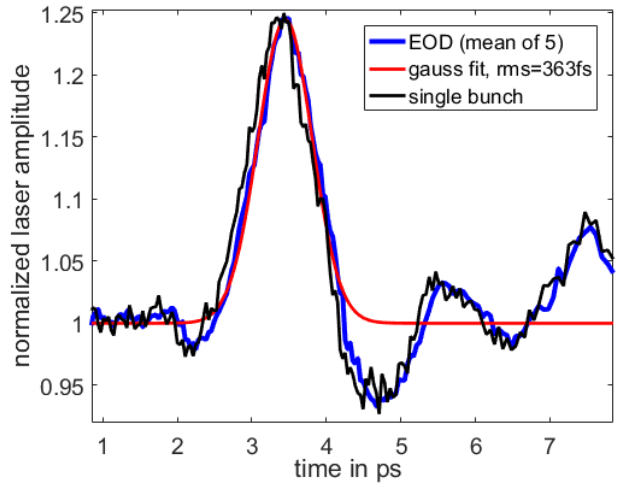


Figure 5: A single-shot EOD measurement together with an average of five consecutive bunches and a Gaussian fit to the average.

Figure 5 shows a single-shot EOD trace from the same data set. The signal from the electron bunch is almost Gaussian with a length of about 360 fs (rms), which is in good agreement with the simulated electron bunch shape for the given accelerator parameters, which are similar but not identical to the design values (Table 1). It is followed by signal components from transverse wake fields that decay over several ten picoseconds.

Measurements over full bunch trains are possible at a bunch repetition rate of 1.13 MHz or 2.26 MHz, whereas at operation of the accelerator at 4.5 MHz only every second bunch can be measured. The bunch lengths and arrival times of individual electron bunches in a 30 bunches long train is shown in Fig. 6 together with the standard deviation of

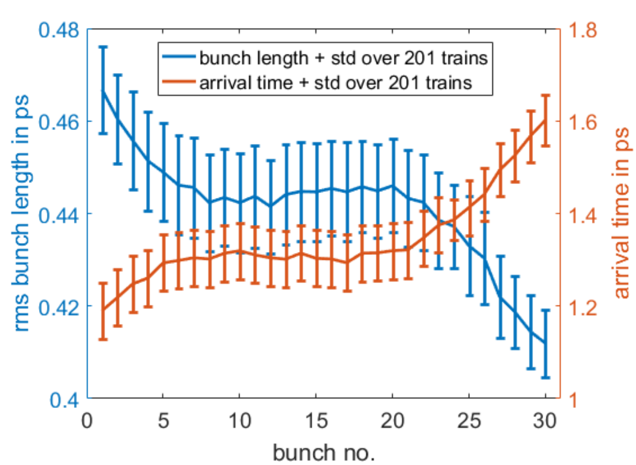


Figure 6: Bunch length and arrival time along the bunch train with a bunch repetition rate of 1.13 MHz.

ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-WEOA03

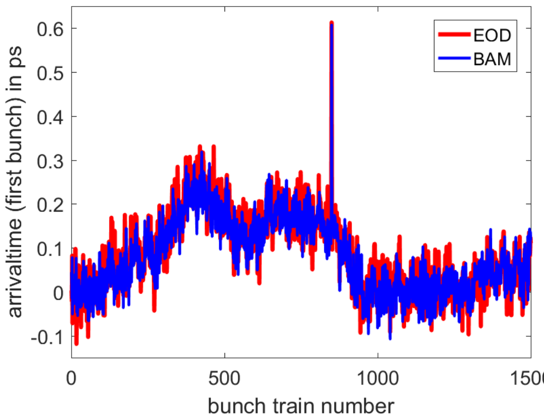


Figure 7: Arrival time of the first bunch in consecutive bunch trains measured with EOD and BAM

the values at each position. The bunch lengths change from 470 fs at the first bunch to 410 fs at the end together with a shift in arrival time by 500 fs caused by a slight shift in bunch energy over the train, leading to a different compression and beam path length in BC1.

The arrival time of the bunches is also measured by a BAM in the direct vicinity of the EOD, and the data is in good agreement. The standard deviation of the difference in the measurements of the arrival time by BAM and EOD is 39.2 fs over the 2.5 minutes shown in Fig. 7. This gives an upper limit for the synchronization jitter of the laser system.

CONCLUSION

A compact EOD system has been developed for the measurement of longitudinal bunch profiles. Apart form the optics set-up, which comprises the GaP crystal holder and is mounted to the electron beam line, all other sub-systems fit into standard 19 " crates with a total of 25 height units. The EOD systems are located inside the accelerator tunnel in the injector and downstream of the first two bunch compression chicanes and installed in radiation shielded racks below the electron beam line in the vicinity of the optics set-up. The spectrometer has been equipped with a MHz line detector [14] to be capable of recording single-shot measurements at 1.13 MHz over full bunch trains.

First measurement results of the EOD system downstream of the second bunch compressor chicane (BC1 in Table 1) have been presented. The measured single-shot bunch lengths are in good agreement with predictions from simulation codes and slightly larger than the predicted design values. The installation of a TDS at this location is delayed but will provide an independent measurement result after installation. The measurement of the distribution of the bunch lengths along the bunch train helps for the optimization of low-level RF regulation and will become especially valuable for setting up long bunch trains of up to 2700 bunches. The results of the measured arrival times are in good agreement with results obtained with a BAM at the same location.

ACKNOWLEDGEMENTS

Special thanks to M. Caselle and L. Rota (KIT, Karlsruhe, Germany) and D. Makowski and A. Mielczarek (DMCS, Łódź University of Technology, Poland) for the great collaboration in developing the KALYPSO and its readout system.

REFERENCES

[1] D. Nölle, "Commissioning of the European XFEL," in *Proc. LINAC18*, Beijing, China, 2018.
[2] G. Feng *et al.*, "Beam dynamics simulations for European XFEL," DESY, Tech. Rep., 2013, TELSA-FEL 2013-04.
[3] C. Gerth, B. Beutner, O. Hensler, F. Obier, M. Scholz, and M. Yan, "Online longitudinal bunch profile and slice emittance diagnostics at the European XFEL," in *Proc. IBIC 2017*, Grand Rapids, USA, 2017.
[4] B. Steffen *et al.*, "Electro-optic time profile monitors for femtosecond electron bunches at the soft X-ray free-electron laser FLASH," *Phys. Rev. ST Accel. Beams*, vol. 12, no. 3, 2009.
[5] M. Viti *et al.*, "The bunch arrival time monitor at FLASH and European XFEL," in *Proc. ICALEPCS 2017*, Barcelona, Spain, 2017.
[6] I. Wilke, A. M. MacLeod, W. A. Gillespie, G. Berden, G. M. H. Knippels, and A. F. G. van der Meer, "Single-shot electron-beam bunch length measurements," *Phys. Rev. Lett.*, vol. 88, p. 124 801, 12 2002.
[7] A. L. Cavalieri *et al.*, "Clocking femtosecond x rays," *Phys. Rev. Lett.*, vol. 94, no. 11, 114801, p. 114 801, 2005.
[8] G. Berden, S. P. Jamison, A. M. McLeod, W. A. Gillespie, B. Redlich, and A. F. G. van der Meer, "Electro-optic technique with improved time resolution for real-time, nondestructive, single-shot measurements of femtosecond electron bunch profiles," *Phys. Rev. Lett.*, vol. 93, p. 114 802, 2004.
[9] B. Steffen, "Electro-optic methods for bunch length diagnostics at FLASH," PhD thesis, University of Hamburg, 2007.
[10] S. Casalbuoni, H. Schlarb, B. Schmidt, P. Schmüser, B. Steffen, and A. Winter, "Numerical studies on the electro-optic detection of femtosecond electron bunches," *Phys. Rev. ST Accel. Beams*, vol. 11, p. 072 802, 7 2008.
[11] F. Müller, S. Hunziker, V. Schlott, B. Steffen, D. Treyer, and T. Feurer, "Ytterbium fiber laser for electro-optical pulse length measurements at the SwissFEL," in *Proc. DIPAC2009*, Basel, Switzerland, 2009.
[12] M. Felber *et al.*, "Compact MTCA.4 based laser synchronization," in *Proc. IPAC2014*, Dresden, Germany, 2014.
[13] B. Steffen, V. Schlott, and F. Müller, "A compact single shot electro-optical bunch length monitor for the SwissFEL," in *Proc. DIPAC09*, Basel, Switzerland, 2009.
[14] L. Rota *et al.*, "KALYPSO: A Mfps linear array detector for visible to NIR radiation," in *Proc. IBIC 2016*, Barcelona, Spain, 2016.
[15] A. Mielczarek *et al.*, "Real-time Data Acquisition and Processing System for MHz Repetition Rate Image Sensors," *IEEE Transactions on Nuclear Science*, vol. in print, 2018.
[16] T. Wilksen *et al.*, "The control system for the linear accelerator at the European XFEL - status and first experiences," in *Proc. ICALEPCS2017*, Barcelona, Spain, 2017.
[17] `https://www.picmg.org/openstandards/microtca/`