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ELECTRO-OPTICAL BUNCH LENGTH DETECTION AT THE EUROPEAN XFEL

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Abstract

The electro-optical bunch length detection system based on electro-optic spectral decoding has been installed and is being commissioned at the European XFEL. The system is capable of recording individual longitudinal bunch profiles with sub-picosecond resolution at a bunch repetition rate of 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 addition, we are testing a second electro-optical detection strategy, the so-called photonic time-stretching, which consists of imprinting the electric field of the bunch onto a chirped laser pulse, and then "stretching" the output pulse by optical means. As a result, we obtain is a slowed down "optical replica" of the bunch shape, which can be recorded using a photodiode and GHz-range acquisition. These tests are performed in parallel with the existing spectral decoding technique based on a spectrometer in order to allow a comparative study.

In this paper, we present first results for both detection strategies from electron bunches after the second bunch compressor of the European XFEL.

INTRODUCTION

The accelerator for the European X-ray Free-Electron Laser (EuXFEL) 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 at electron bunch energies of 130 MeV,700 MeV, and 2.4 GeV, respectively, in between the four accelerating sections.

Electro-optical bunch length detection (EOD) [2] 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. The measurements presented in this paper were performed at the EOD system downstream of the second bunch compressor at a beam energy of 700 MeV and with an expected bunch length of around 250 ps.

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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.

For the EOD system at the EuXFEL the spectrally resolved electro-optical detection technique (EOSD) was chosen. It uses a chirped laser pulse, where the frequency components of a broadband laser pulse are sorted in time. The temporal profile of the modulation can be retrieved from its modulated spectrum using the known relationship between wavelength and longitudinal (temporal) position in laser pulse [3]. It has been shown that sub-ps electron bunches of about 100 pC charge can be measured with about 200 fs resolution using EOSD [2, 4].

Temporally [5] and spatially [6] resolved detection offer a higher 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. For a more comprehensive description of electro-optical detection techniques and theory see [4, 7]. The maximum rate of all techniques is limited by both the repetition rates of the laser system and (line) detector.

To measure single shot laser spectra as needed for EOSD with a high repetition rate, currently two different techniques are available. One can use a spectrometer with a high-speed line camera like the KALYPSO detector [8]. The KALYPSO detector can measure spectra with an repetition rate up to 2.7 MHz and was used previously to measure bunch length in the EOSD systems at the European XFEL [9]. Alternatively one can stretch the picosecond short laser pulse in a fiber of known dispersion to a length of several nanoseconds and measure the temporal profile of the laser pulse with a fast photodiode and gigahertz bandwidth oscilloscope, known as photonic time-stretch [10]. Photonic time-stretch has first be proposed for recording GHz-range RF signals [11]. The principle has been then applied to electro-optic sampling of free-propagating CSR THz pulses at SOLEIL [12], and more

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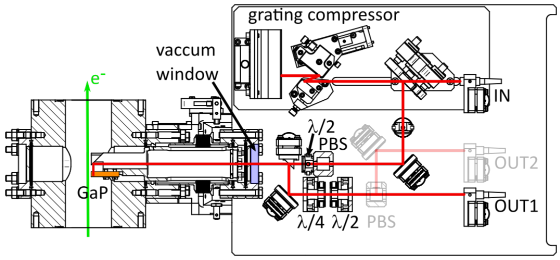

Figure 1: Assembly drawing of the optics set-up at the electron beam line including the vacuum chamber (left). PBS: polarizing beam splitter.

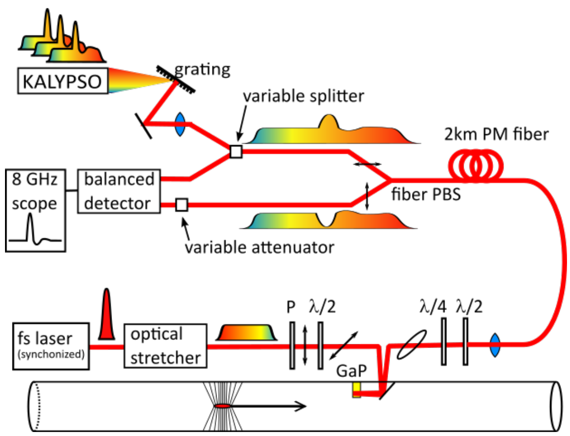

Figure 2: Schematic drawing of a spectrally encoded electro-optical detection setup including the single shot spectrometer and the photonic time-stretch detector. P: polarizer; PBS: polarizing beam splitter.

recently electron bunch near field at KARA [13]. Given the inherent high repetition rate capability of photonic time-stretch, it appears relevant to test the method in the high-repetition rate Free-Electron Laser context, and compare its performances with respect to spectrometer-based electro-optic sampling.

To compare both techniques, the existing EOSD set up was modified to allow applying both techniques in parallel.

MODIFICATIONS OF THE EOSD SYSTEM AT THE EUROPEAN XFEL

Most parts of the EOSD system described earlier [9] remained unchanged, including the Ytterbium fiber laser system and its synchronization, the spectrometer with the KALYPSO MHz line detector, the vacuum chamber with the 2 mm thick GaP crystal, and the MicroTCA.4 [14] crate with the analogue and digital boards for laser synchronization and data readout.

At the optics set-up at the electron beam line vacuum chamber the free-space polarizing beam splitter (PBS) and the following two single-mode fiber couplers were replaced by a fiber coupler (Fig. 1) coupling the laser into a two kilometer long polarization maintaining (PM) fiber. The laser pulse with its polarization modulated in the GaP crystal by

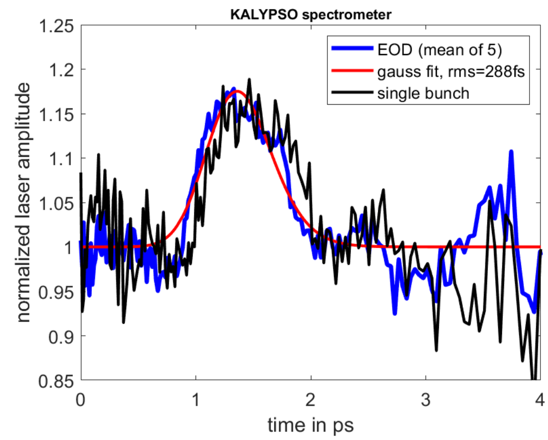

Figure 3: A single-shot EOD measurement from the spectrometer together with an average of five consecutive bunches and a Gaussian fit to the average.

the electric field of the electron bunch is stretched to several nanoseconds in the long fiber and afterwards it is split into its orthogonal polarizations by a fiber PBS. The two polarizations are guided to the two inputs of a balanced photodetector with 20 GHz bandwidth (DSC-R412, Discovery Semiconductors Inc., USA). Both arms hold a variable attenuator each to adjust the optical power level to the dynamic range of the detector. One of the attenuators is realized as an variable splitter which can also be used to send one polarization to the single shot spectrometer, alternatively (see Fig. 2). The electrical outputs of the balanced photodetector are connected to a 8 GHz Agilent oscilloscope to measure and store the data.

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 for the spectrometer as well as a measurement of the stretch factor for the photonic time-stretch.

FIRST MEASUREMENTS

Figure 3 shows a single shot measurement from the KALYPSO spectrometer together with an average of five consecutive bunches and a Gaussian fit to the averaged signal. The electron bunch had a charge of 250 pC and was measured to have an approximate bunch length of 290 fs (rms), which is in good agreement with the simulated electron bunch shape for the given accelerator parameters. However the signal-to-noise ratio (SNR) is significantly decreased as compared to measurements done before the modification of the EOSD setup (Fig. 4). We attribute this to the additional attenuation and disturbances in the spectrum from the long PM fiber and other fiber components (especially the fiber PBS) leading to

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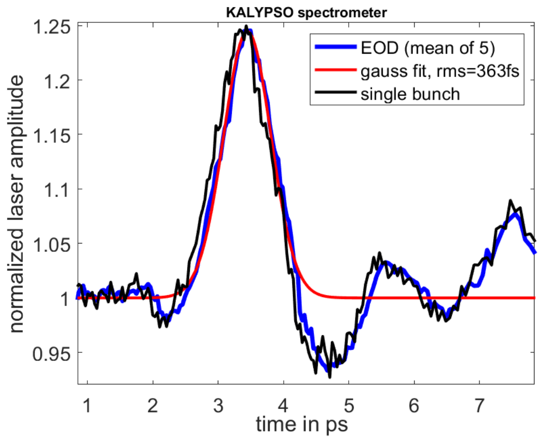

Figure 4: A single-shot EOSD measurement from the spectrometer with the EOSD setup before modification showing a significantly better SNR. Here the bunch charge was 500 pC.

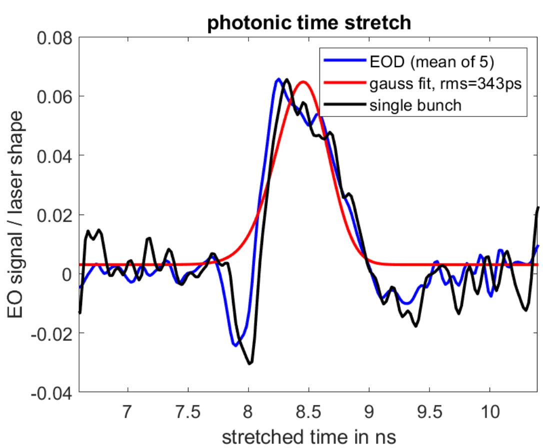

Figure 5: A single-shot EOSD measurement recorded with photonic time-stretch.

a reduced laser power at the line detector and a less stable spectrum with reduced bandwidth.

The corresponding measurement recorded with photonic time-stretch is shown in Fig. 5. The data was measured approx. 30 minutes before the data shown in Fig. 3 at identical accelerator settings. It shows an approximate bunch length of 340 fs (rms), which is slightly longer than measured with the spectrometer measurement.

The laser spectrum recorded with photonic time-stretch without modulation from the electron beam shows significant modulation due to interferences, which are most likely caused by the insufficient performance of the fiber polarizing beam splitter (Fig. 6), leading to some additional artifacts in the reconstructed bunch shape.

CONCLUSION AND OUTLOOK

The EOSD setup at the European XFEL was modified to test two different techniques to capture single shot spectra of the modulated laser pulses with MHz repetition rate, a spectrometer with a MHz line detector and a photonic

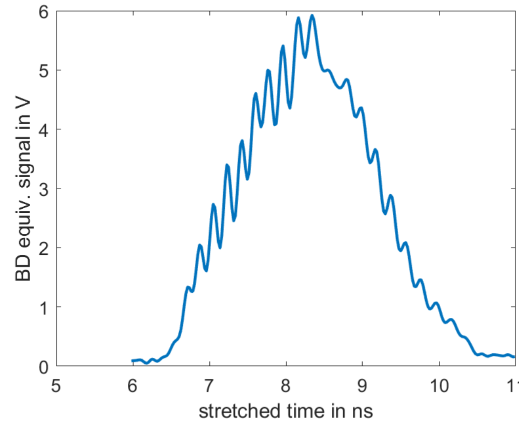

Figure 6: Laser spectrum recorded with photonic time-stretch without modulation from the electron beam.

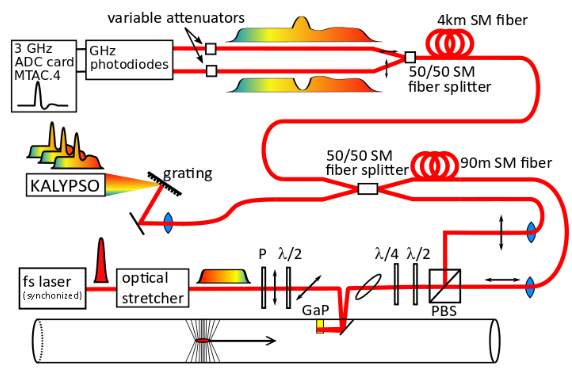

Figure 7: Schematic drawing of a spectrally encoded electro-optical detection setup. P: polarizer; PBS: polarizing beam splitter.

time-stretch technique. Both approaches can measure the bunchlength with the required repetition rate of 1.13 MHz and an estimated resolution of some 10 fs, however both suffer from unwanted distortions and losses due to PM fiber components in the current setup, which limits the possibility to compare the performance of both approaches.

A new setup (Fig. 7) is currently installed which is based purely on SM fiber components. The splitting of the orthogonal polarizations is done by a free-space PBS directly at the beamline again, which has proven to have the better performance. In addition the laser pulse in one polarization is delayed by 440 ns (half of the pulse spacing of the laser) before both polarizations are combined again and sent to the two detectors in parallel. Since both detectors can sample with 2.2 MHz, both polarizations, carrying modulations of opposite sign, can be measured and used for the electron pulse reconstruction.

In addition it is planned to exchange the oscilloscope to an fast MTCA based ADC card (ADQ7DC, Teledyne Signal Processing Devices, Sweden) to integrate the readout into the EuXFEL control system.

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