A COMPACT ELECTRO OPTICAL BUNCH LENGTH MONITORING SYSTEM - FIRST RESULTS AT PSI

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Abstract

Electro Optical (EO) sampling is a promising non-destructive method for measuring ultra short (sub picosecond) electron bunches. A prototype of a compact EO bunch length monitor system for the future SwissFEL facility was designed and built at PSI. Its core components are an optical setup including the electro optically active crystal and an Ytterbium fiber laser system which emits broadband pulses at 1050nm. The setup allows the direct time resolved single-shot measurement of the Coulomb field (THz-radiation) of the electron beam - and therefore the bunch length - for bunches as short as 200 fs. The new monitoring system is described in detail and first experimental results from the SLS injector are presented.

INTRODUCTION

Paul Scherrer Institute is planning a free electron laser for X-Ray wavelengths, the SwissFEL. The baseline design foresees to generate electron bunches with a charge between 200 and 10 pC and bunch lengths between 10 ps and a few fs. These bunches will be accelerated in a normalconducting linear accelerator (linac) to a particle energy of up to 6 GeV to radiate coherently at wavelengths between 0.1 and 7 nm in one of the two undulators. To test the feasibility of novel accelerator concepts and components needed for the generation of such high-brightness beams, their longitudinal compression and the preservation of the emittance, a 250 MeV Injector is currently being commissioned at PSI (see Fig. 2).

Precise measurements of the temporal profile of extremely short electron bunches are indispensable for a detailed understanding of the bunch compression and lasing mechanisms in a FEL. Single-shot electro-optical (EO) detection techniques are ideally suited for this purpose since they are non-destructive and can be carried out during regular operation of the free-electron laser for user experiments [1, 2]. An important aspect is that they permit correlation studies between the measured time profile of electron bunches and other measured beam parameters as well as the properties of FEL pulses produced by the same bunch. A second technique for the single-shot direct visualization of longitudinal electron bunch profiles are transverse-deflecting structures (TDS) [3]. The TDS converts the temporal profile of the electron bunch charge density into a transverse streak on a view screen by a rapidly varying electromagnetic field. The measurement with the TDS offers the highest resolution but is inherently destructive, so it cannot be used as an online monitor of the bunch length.

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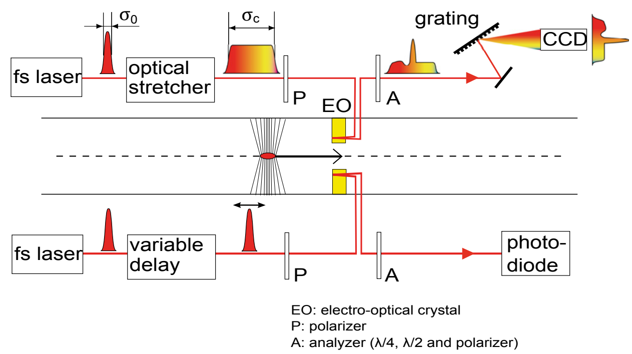

Figure 1: Schematic drawing of a spectrally encoded electro-optical detection setup (top) and electro-optical sampling setup (bottom).

EO BUNCH LENGTH DETECTION

When a relativistic picosecond duration bunch passes within a few millimeters of an electro-optic crystal, its transient electric field is equivalent to a half-cycle THz pulse impinging on the crystal. The temporal profile of this equivalent half-cycle THz pulse provides a faithful image of the longitudinal charge distribution inside the electron bunch if the electrons are highly relativistic. The transient electric field induces birefringence in the electro-optic crystal. As the electric field propagates through the crystal, the birefringent properties of the crystal also propagate. This birefringence can be probed by a copropagating optical laser pulse [2].

Several variants of EO bunch diagnostics have been applied in electron bunch diagnostics [4, 5, 6], all sharing the underlying principle of utilizing the field-induced birefringence in an electro-optic crystal to convert the time profile of a bunch into a spectral, temporal, or spatial intensity modulation of a probe laser pulse.

THE COMPACT EO MONITOR

The presented compact EO bunch length monitor utilizes the spectral decoding technique, where the bunch shape information is encoded into a chirped laser pulse and then retrieved from its modulated spectrum using the known relationship between wavelength and longitudinal (temporal) position in laser pulse.

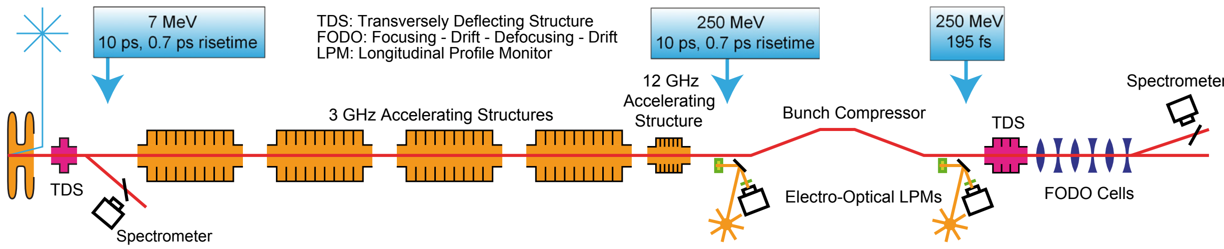

Figure 2: Schematics of the 250 MeV injector with the planned bunch length diagnostics

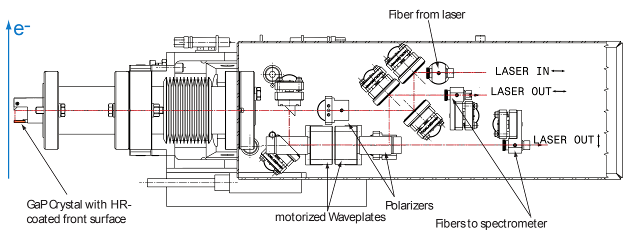

Figure 3: Assembly drawing of the compact EO monitor

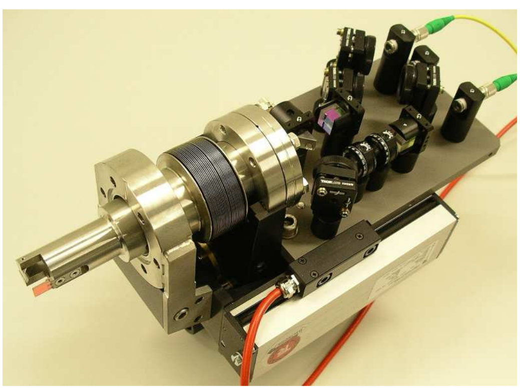

Figure 4: Photo of the EO monitor including the optics

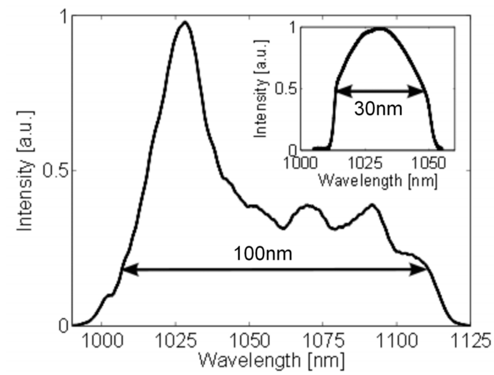

Figure 5: Broad spectrum of the amplifier as used for the EO monitor. Inset: Spectrum of the oscillator.

The chirped laser pulse passes through the polarizer and the EO crystal in the beampipe, where the polarization becomes elliptical. The ellipticity of the polarization is proportional to the electric field of the electron bunch and has the same temporal structure. The analyzer, a combination of wave plates and a polarizer, turns the elliptical polarization into an intensity modulation. The longitudinal charge distribution gets encoded in the spectrum of the laser pulse, which can then be detected using a spectrometer (Fig. 1).

Alternatively the unchirped laser pulse and be used and the delay between laser and electron pulse is varied to sample the Coulomb field. In this scheme a photo diode can be used as a detector, which has a better ignal to noise ratio than the infrared line camera needed for EOSD, especially at low laser intensity.

The EO crystal used here is a Galliumphosphide (GaP) crystal with a reflective coating for the laser wavelength (1050 nm) at the front surface (towards the electron source) and an antireflective coating at the backside. Depending on the expected bunch length the monitor can be equipped with crystals of different thickness up to 5 mm. The laser enters the crystal at the backside, is reflected at the frontside and leaves the crystal at the backside again, while the Coulomb field of the electron bunch enters at the frontside, propagating towards the backside. This way the laser first counterpropagates with the electric field pulse of the bunch and afterwards copropagates. This leads to some artifacts in the EO signal shown in the next section, but the monitor can be build very compact and a an upstream mirror can be avoided that would disturb the Coulomb field and trigger wakefiels, which would also lead to spurious EO signals. The total length of the monitor including the space for the optic elements is less then 150 mm.

The crystal and the downstream mirror are mounted on a holder which is mounted on a motorized vacuum-feedtrough (Fig. 3 and 4). Outside the vacuum a small breadboard is fixed to the feedthrough which holds the required optics including the fibercouplers. This way all optic 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 beampipe.

As laser source for the monitor an amplified Yb-doped fiber laser system has been developed at the University of Bern. It delivers pulses with 20 to 200 nJ pulse energy and up to 100 nm useful bandwidth (Fig. 5). Details of the laser system and the synchronization to the accelerator are described elsewhere [7].

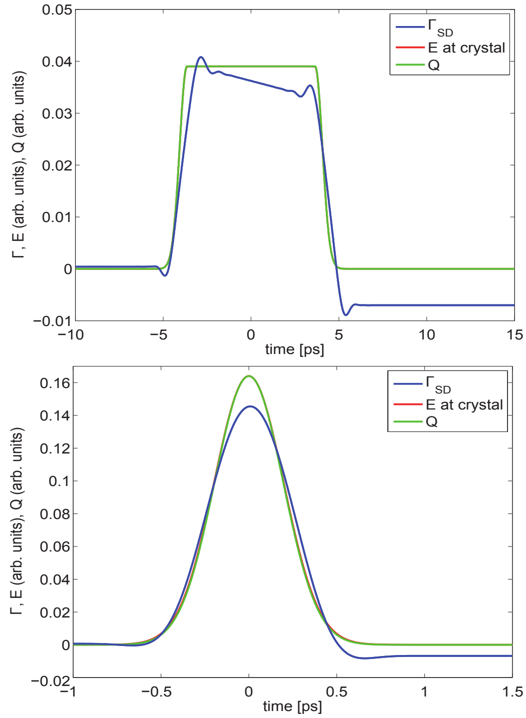

Figure 6: Simulated EO signals at different positions of the 250 MeV injector: before the bunch compressor (top, for a 2 mm thick GaP crystal and a laser pulse chirped to 5 ps), and after the bunch compressor (bottom, for a 0.5 mm thick GaP crystal and a laser pulse chirped to 500 fs). Note the different time scale.

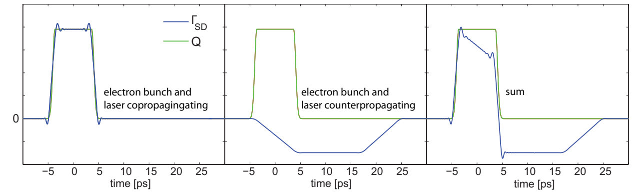

Figure 7: Simulated EO signals from a 10 ps long electron bunch passing a 1 mm thick GaP crystal, modulated on a copropagating laser pulse (left), a counterpropagating laser pulse (center) and the sum of the two (right).

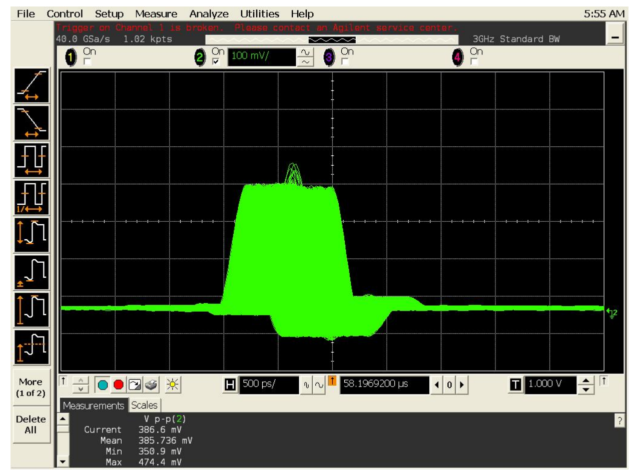

Figure 8: First EOS signals of the CEOM at the SLS linac

SIMULATIONS

The EO signals expected for the different positions along the 250 MeV injector have been simulated using a code based on the geometric response function [1, 8]. In the low energy region (7 MeV) right after the gun the measurement would be dominated by broadening due the $1/\gamma$ opening angle of the Coulomb field (less than 2 ps resolution for 3 mm distance), therefore no EO monitor is foreseen here. For the high energy region (250 MeV) before and after the bunch compressor the bunch shape can be well determined except from a shift of the baseline of the measurement after the bunch signal as shown in Fig. 6 for a distance of 3 mm between the path of the electron beam and the path of the laser.

This shift is due to an additional polarization rotation which the laser pulse accumulates when it sees the counter-propagating field of the electron bunch before the laser is reflected at the front surface of the EO crystal. This rotation is smaller in amplitude and of opposite sign as the rotation accumulated when the laser and bunch field are copropagating (Fig. 7). The relative amplitude of the two decreases with shorter electron bunches and thicker crystals. As long as the electron bunch is significantly shorter than the EO crystal multiplied with its refractive index, the signal coming from the part where the laser is copropagating can be well reconstructed from the sum signal. The effect in Fig. 7 is exaggerated by picking a short crystal and a long electron pulse.

MEASUREMENTS

For first tests the CEOM was equipped with a 1 mm thick GaP crystal and included in the diagnostic section at the end of the SLS injector. It is a warm 3 GHz linac with a thermionic gun that produces up to 1 nC electron bunches with 3 Hz repetition rate. The bunches are accelerated to 100 MeV and compressed to a bunch length of 2 to 20 ps at the diagnostic section. The Ytterbium fiber laser system is placed outside the linac buncer and connected to the monitor via 17 m of polarization maintaining fiber. The modulated laser pulses after the CEOM are coupled again into optical fibers and transported to the detector outside the bunker.

The measurements were done using the electro-optical sampling technique with variing delay in a 'near crossed polarisation' setup. The laser pulses were pre-chirped at the laser and then compressed by the disperion in the fiber to less than 300 fs. The detection was done with a fast InGaAs photodiode connected to a oscilloscope (Fig. 8).

First measurements using a vector modulator of the laser synchronization to change the delay between laser and electron bunch in steps of 490 fs show a 2 ps long signal

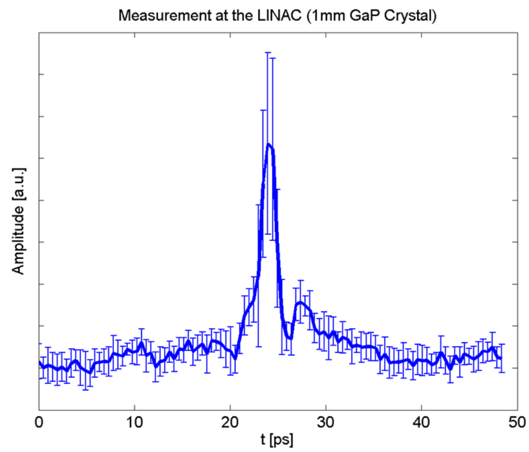

Figure 9: Scanned EO signal, average and standard deviation over 20 measurements. The delay is varied by a vector modulator in 490 fs steps. The large variation at the peak is due to arrivaltime jitter of the electron bunch.

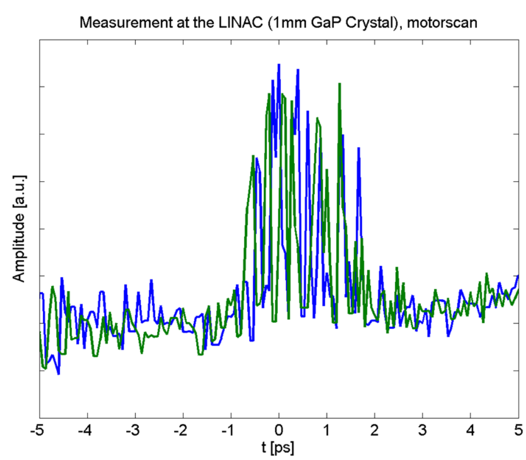

Figure 10: Scanned EO signal, blue: forward scan, green: backward scan. The delay is varied by a delay stage in 67 fs steps.

with large amplitude fluctuations (Fig. 9). A measurement with finer stepsize (67 fs) using an optical delay line in the laser path without averaging (Fig. 10) reveals that even at the correct delay only approximately every second bunch produces an EO signal. This effect is due to a large arrivaltime jitter of the electron bunch, which is in the same order of magnitude as the bunch length. The arrivaltime jitter expected from the timing jitter of the gun together with the bunching system is in about 2 ps, while other possible sources of the large amplitude fluctuations in the EO signal, like bunch charge or shape fluctuations could be excluded by other measurements. The averaged EO signal in Fig. 9 is therefore a convolution of the electron bunch shape and the arrivaltime jitter and the measurements supports the assumption that the contributions of both are approximately of equal size, but currently no independent bunch length monitor is available at the SLS linac. For a detailed study single shot bunch length measurements are needed, but EOSD measurements could not be performed yet due to the late arrival of the infrared line camera (see [9] for single shot EOSD measurements at the SLS-IR beamline).

CONCLUSION

A first prototype of a compact electro-optical bunch profile monitor has been built and was tested at the SLS linac. A second monitor is beeing comissioned at FLASH using a commercial laser system [10]. In parallel a packaged version of the laser for operation at the 250 MeV injector which is currently commissioned to improve stability and reliability.

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