A COMPACT SINGLE SHOT ELECTRO-OPTICAL BUNCH LENGTH MONITOR FOR THE SwissFEL

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Abstract

The knowledge and control of electron bunch lengths is one of the key diagnostics in XFEL accelerators to reach the desired peak current in the electron beam. A compact electro-optical monitor was designed and build for bunch length measurements at the SwissFEL. It is based on a mode locked ytterbium fiber laser probing the field-induced birefringence in an electro-optically active crystal (GaP) with a chirped laser pulse. 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 - with an accuracy as good as 200 fs. Simulations of the signals expected at the SwissFEL will be presented.

INTRODUCTION

Paul Scherrer Institut 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 assembled 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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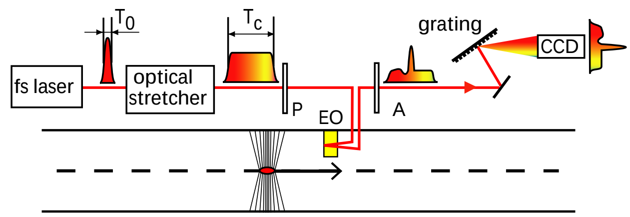

Figure 1: Schematic drawing of a spectrally encoded electro-optical detection setup. P: polarizer; EO: EO crystal; A: analyzer.

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.

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

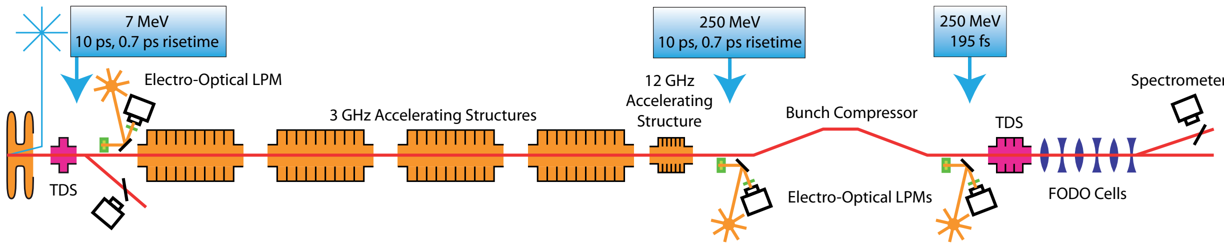

Figure 2: Schematics of the 250 MeV injector with the planned bunch length diagnostics. TDS: Transversely Deflecting Structure; FODO: Focusing - Drift - Defocusing - Drift; LPM: Longitudinal Profile Monitor.

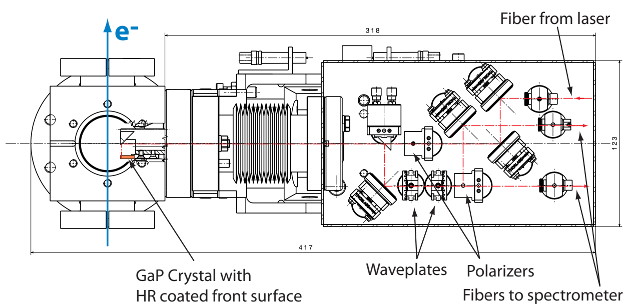

Figure 3: Assembly drawing of the compact EO monitor including the vacuum chamber (left).

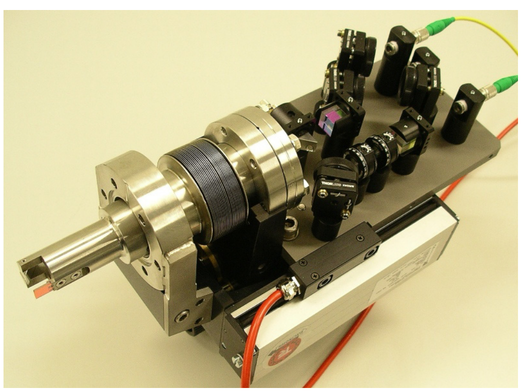

Figure 4: Photo of the EO monitor including the optics.

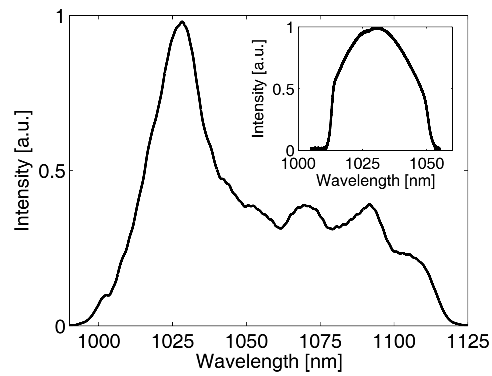

Figure 5: Broad spectrum of the amplifier as used for the EO monitor. Inset: Spectrum of the oscillator.

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).

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].

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

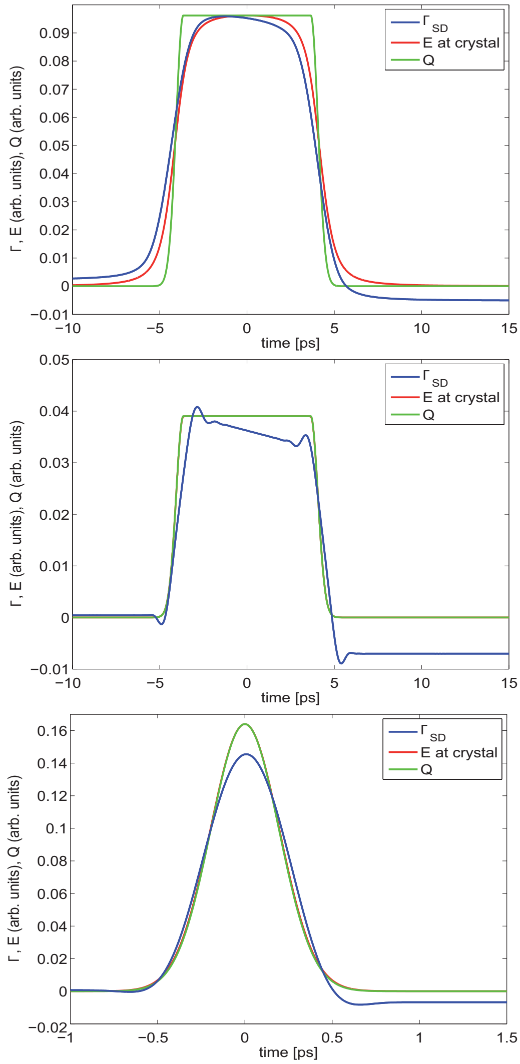

Figure 6: Simulated EO signals at different positions of the 250 MeV injector: after the gun (top, for a 5 mm thick GaP crystal and a laser pulse chirped to 5 ps(rms)), before the bunch compressor (center, for a 2 mm thick GaP crystal and a laser pulse chirped to 5 ps), and after the bunch compressor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

low energy region (7 MeV) right after the gun the dominant broadening is due the $1/\gamma$ opening angle of the Coulomb field, shown in Fig. 6 (top) for a distance of 3 mm between the path of the electron beam and the path of the laser. 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 (Fig. 6 (center and bottom)).

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.

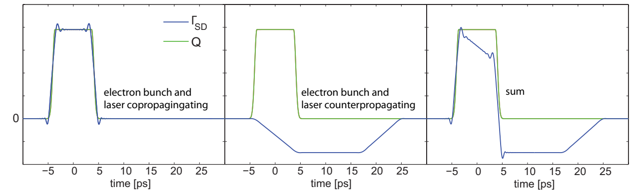

Figure 7: Simulated EO signals from a 10 ps long electron bunch passing a 1 mm thick GaP crystal, modulated on a copropagating laser pulse (left), a counterpropagating laser pulse (center) and the sum of the two (right).

CONCLUSION

Prototypes of the monitor and the laser have been build and are ready for first tests planned at the SLS linac in summer 2009. Further optimizations can be done by measuring shorter pulses during FEMTO slicing. In parallel we are planning a packaging of the laser for operation at the 250 MeV injector which is currently under construction.

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