FS-SYNCHRONIZATION AND ELECTRON BUNCH LENGTH MEASUREMENTS AT THE SLS PRE-INJECTOR LINAC

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The bunch length of the electron beam has been measured at the end of the SLS pre-injector LINAC with sub-ps time resolution by means of electro-optical sampling using a fs Ti:Sa laser pulse and coherently emitted transition radiation. Synchronization between the accelerator radio frequency at 500 MHz and the laser repetition rate of 81 MHz has been achieved by phase-locking with a relative timing jitter of less than 40 fs rms. The electron bunch length was measured to be 3.3 ps (FWHM) with an estimated time resolution of 330 fs rms.

INTRODUCTION

Within the framework of a collaboration between DESY and PSI on electron bunch length measurements, it has been arranged to set-up a 15 fs Ti:Sa laser system at the 100 MeV SLS pre-injector LINAC with the objectives to develop an ultra precise synchronization between the accelerator radio frequency (RF) and the laser repetition rate and to perform electro-optical (EO) bunch length measurements with sub-ps time resolution. Both topics are well integrated in top priority research projects at DESY and PSI representing important contributions to the success of the VUV and X-ray Free Electron Lasers at DESY [1] and the fs-pulse slicing project at PSI [2]. Electro-optical bunch length measurements make use of the Pockels effect - a birefringence in non-linear optical crystals, which is induced by external electric fields. At SLS, the electric fields have been generated by transition radiation (TR), which is coherently emitted in the THz-regime, when short (ps or sub-ps) relativistic electron bunches cross the interface between two media with different electric properties. The initially linear polarized Ti:Sa laser radiation is converted into elliptical polarization in case of coincidence between the laser pulse and the transient CTR field in the EO-crystal. The polarization changes depend on the electric field strength in the crystal and can be measured with a suitable detection scheme. By shifting the arrival time of the short (fs) laser pulses relative to the ps long CTR field in the EO-crystal, a sampling of the longitudinal density profile of the electron bunches can be obtained. The resulting time resolution of such EO-sampling techniques is mainly determined by the width of the optical laser pulses and the relative timing jitter between laser and electron bunches.

EOS EXPERIMENTAL SET-UP

The Ti:Sa laser used in this experiment provides 15 fs long pulses at a repetition rate of 81 MHz. The central wavelength is at 800 nm with a bandwidth of 65 nm. Synchronization mode-locking and stability of the laser system has been set-up on a vibration-damped optical table in the SLS technical gallery. The laser beam is transported into the LINAC bunker through a 15 m long optical transfer line, which is equipped with five mirrors and two lenses (f = 4 m) to image the beam onto an optical table in front of the SM5 optical monitor of the SLS pre-injector LINAC. Fig. 1 shows a schematic layout of the experimental set-up in the LINAC bunker.

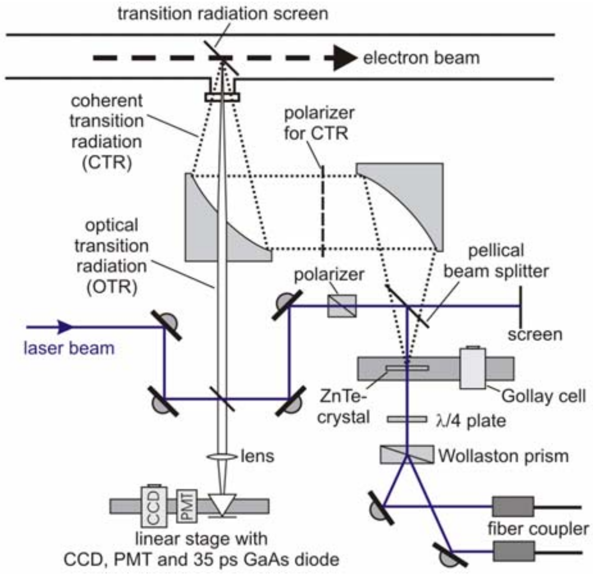

Fig. 1: Schematic layout of the EOS experimental set-up at the ALIDI-SM5 optical monitor behind the 100 MeV SLS pre-injector LINAC.

The remotely controllable TR radiator - a 380 μm thick silicon wafer with 1 μm thick Al coating - is mounted at an angle of 45° in a DN63CF UHV-cube, which allows to couple out the radiation through a crystalline quartz window of 63 mm diameter. The visible part of the TR, which is emitted in a relatively narrow cone of ~ 2/γ (with γ = 200), is passing through a central hole in the first, collimating parabolic mirror (f = 250 mm) and is focused onto a fast photomultiplier, where a coincidence measurement with part of the Ti:Sa laser beam is used for coarse synchronization adjustment between the electron bunches and the laser pulses. The coherent, long wavelength part of the TR, which is emitted in a much wider opening angle due to diffraction effects [3], is collimated by a first parabolic mirror, passes a wire grid polarizer for selection of the horizontal polarization and is focused onto a ZnTe crystal by a second parabolic mirror (also f = 250 mm). The Ti:Sa laser beam, which can be remotely adjusted through picomotor driven mirrors, is passing a Glan-Thomsen polarizer to compensate for polarization changes in the beam transfer system and is reflected onto the EO-crystal through a pellicle beam splitter. The ZnTe crystal, which becomes birefringent in the presence of strong (> 1 kV/cm) electric fields, is cut in the (110) plane with the crystallographic (-1,1,0) axis oriented horizontally. When the horizontally polarized CTR and Ti:Sa laser pulses coincide in the crystal, a polarization change (from horizontal to elliptical) of the laser radiation is induced. The resulting signal intensity, which is acquired by a balanced detection scheme, depends on the electro-optic coefficient r_{41} of ZnTe and the strength of the electric field. A more detailed view of the EOS detection scheme is shown in Fig. 2.

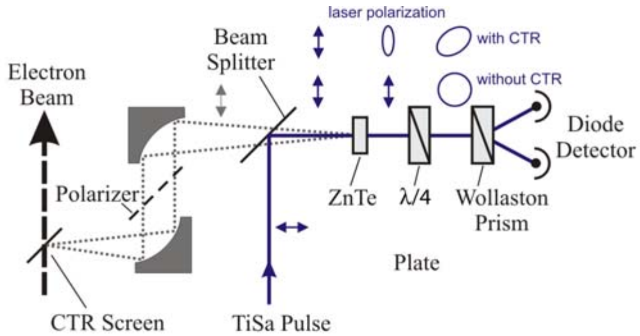

Fig. 2: Detailed view of the EOS signal detection scheme using a quarter-wave plate, Wollaston prism and a balanced diode detector. The laser and the CTR radiation are polarized horizontally, parallel to the (-1,1,0) axis of the ZnTe crystal. The polarization vectors along the experiment are indicated with (top) and without (bottom) CTR.

A quarter-wave plate and a Wollaston prism separate the two orthogonal polarization components of the laser beam behind the EO-crystal. Both polarization components are guided separately into two motorized fibre couplers and are transferred outside the LINAC bunker onto the optical table in the SLS technical gallery, where the balanced diode detector is located to minimize signal distortion due to electro-magnetic noise in the LINAC bunker.

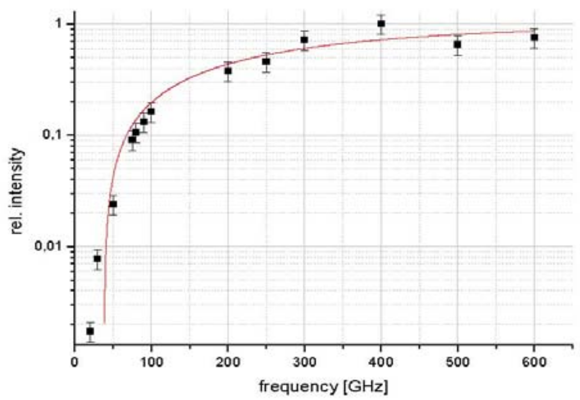

Fig. 3: Computed transfer function for CTR from the radiator (screen) to the ZnTe crystal. The convolution of the finite (σ = 2 mm) laser and CTR spot sizes in the EO-crystal leads to a strong suppression of low frequencies.

The CTR emission process at the ALIDI-SM5 optical monitor, as well as the transfer from the TR screen to the ZnTe crystal, have been described by an analytical model and could be verified during previous measurement campaigns [3]. Effects like water absorption and diffraction limitations due to apertures, finite size of optical elements and the spatial overlap between laser and CTR in the ZnTe crystal have been considered to obtain a frequency dependent transfer function. Fig. 3 shows the computations, which were performed with the optics code ZEMAX, yielding a strong suppression of frequencies below 50 GHz.

SYNCHRONIZATION

The minimum time resolution, which can be achieved with EOS is determined by the thickness of the EO-crystal, the laser pulse length and the accuracy of the synchronization between the laser and the electron respectively CTR pulses. The selection of the crystal thickness depends mainly on the expected CTR field strength and the corresponding polarization change of the laser when passing the EO-crystal. Crystal thicknesses should ideally match the range of the expected electron bunch length and typically range from 100 μm to 1 mm. The laser pulse duration is of course another limiting factor and should be selected as short as possible (in case of the SLS experiment 15 fs). The synchronization between the laser (repetition rate) and the electron bunch (RF frequency), as well as the precise control of the relative timing are the most critical issues in case of EOS experiments. For the SLS measurements, this turned out to be a considerable challenge, since the LINAC RF at 500 MHz has no sub-harmonics close to the Ti:Sa laser repetition rate of 81 MHz. Therefore, a reference frequency of 3.5 GHz had to be chosen, where the 7^{th} harmonic of the LINAC RF was locked to the 43^{rd} harmonic of the laser repetition rate by using a single phase-locked-loop (PLL). A schematic layout of the synchronization unit and a short description of its functioning can be taken from Fig. 4.

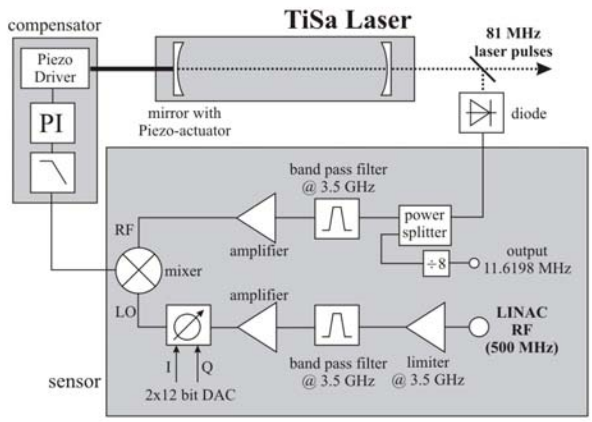

Fig. 4: Schematic layout of the EOS synchronization unit. Part of the laser pulses are directed by a beam splitter to a 10 GHz photo diode. The 43^{rd} harmonic of the diode signal is selected and mixed with the 7^{th} harmonic of the LINAC RF. Down-conversion (to DC) of the 3.5 GHz reference frequency results in an error signal, which is fed back to the piezo controlled cavity mirror of the Ti:Sa laser resonator. Regulation of the cavity length respectively the laser repetition rate is

accomplished via a PI controller.

The 3.125 Hz repetition rate of the SLS injector system is usually synchronized to the 50 Hz line frequency for stability reasons. In case of the EOS measurements it was required to derive the LINAC gun trigger from the Ti:Sa laser to ensure coincidence for each electron and laser pulse.

MEASUREMENTS AND RESULTS

The stability of the synchronization between the Ti:Sa laser repetition rate and the LINAC RF frequency has been determined by a frequency analysis of the mixer error signal, which is shown in Fig. 5. The integrated spectral power density in the frequency range between 0.5 Hz and 106.5 kHz was used to compute the rms time jitter of the synchronization to about 35 fs. The relative jitter between the electron bunches and the LINAC RF is dominated by the quality of the optical receiver at the gun and not included in this treatment. It has been measured to 330 fs over a time span of five minutes by analyzing the amplitude fluctuations of the balanced detector signal when laser pulse is put on the rising edge of the CTR signal, assuming a linear dependence between time and amplitude on the flank of the signal.

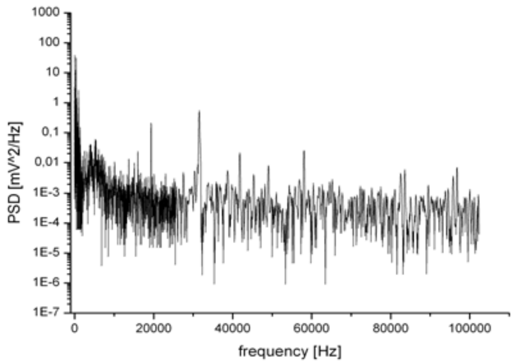

Fig. 5: Noise spectrum of the mixer error signal.

The EOS measurements were conducted in three steps. First, the coarse time overlap between the laser and the optical part of the TR pulses was adjusted on a photomultiplier to about 200 ps. Then, coincidence between the coherent, long wavelength part of the TR and the Ti:Sa laser pulses in the ZnTe EO-crystal was achieved by scanning the arrival time of the electron bunches relative to the laser pulses in ps steps. Once the signal was found on the balanced detector, a narrow time interval was scanned in 200 fs steps and each recorded point was averaged over 10 consecutive bunches. The result of a typical EOS scan is shown in the upper part of Fig. 6. The reconstruction of the effective longitudinal density profile of the electron bunches behind the 100 MeV SLS pre-injector LINAC was accomplished in the following way. A possible bunch shape was assumed and Fourier transformed, including the transfer function in Fig. 3. The resulting frequency spectrum was Fourier back-transformed (curve in Fig. 6) and compared to the measured signal by means of a χ^2 fit. The lowest χ^2, respectively the best approximation was found for an assumed bunch profile composed of three Gaussian pulses as shown in the lower part of Fig. 6. The bunch length amounts to 3.3 ps (FWHM) with an estimated overall time resolution of 330 fs.

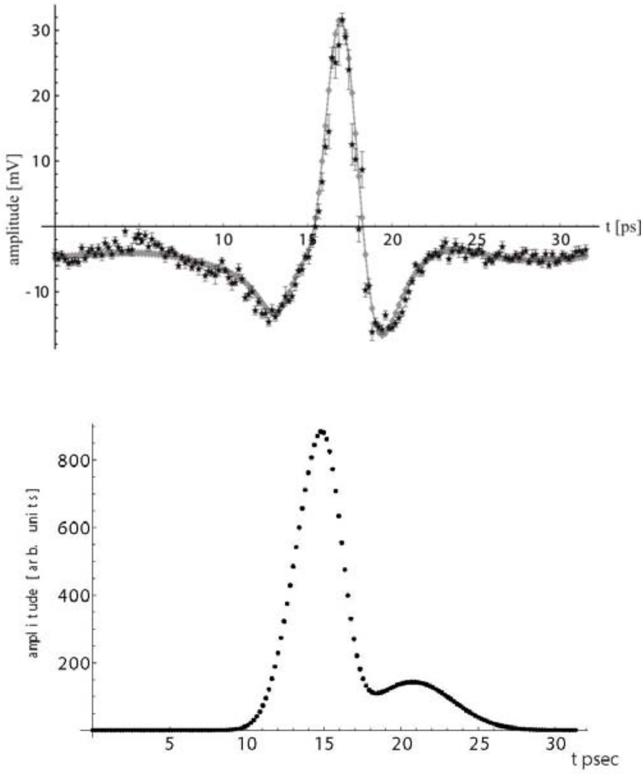

Fig. 6: Top: measured time profile (black stars) and fitted bunch profile (grey curve) of the CTR pulses at the ALIDI-SM5 optical monitor behind the SLS pre-injector LINAC. Bottom: fitted bunch profile for EOS measurements composed of three Gaussian pulses.

CONCLUSIONS AND OUTLOOK

The EOS technique has been successfully applied for bunch length measurements at the SLS LINAC. A synchronization accuracy of better than 40 fs between the laser repetition rate and the LINAC RF has been achieved and electron bunch lengths on the order of 3 ps (FWHM) could be measured behind the 100 MeV SLS pre-injector LINAC. Similar EOS measurements will be performed at the VUV-FEL at DESY, while EO autocorrelation measurements [4] with the potential of single shot bunch length determination are in preparation at PSI.

REFERENCES

[1] For more information see: http://xfel.desy.de and http://www-hasylab.desy.de/facility/fel/vuv

[2] G. Ingold et. al., *Sub-Picosecond Optical Pulses at the SLS Storage Ring*, PAC 2001, Chicago, USA, p. 2656.

[3] D. Sütterlin et. al., *Development of a Bunch Length Monitor with Sub-Picosecond Time Resolution and Single Shot Capability*, Proc. DIPAC 2003, Mainz, Germany, p. 228.

[4] D. Sütterlin, PhD thesis in preparation.