Bunch length measurements at the SLS Linac using Electro Optical Techniques

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Abstract

An electro-optic sampling experiment has been carried out at the 100 MeV electron linac of the Swiss Light Source. Coherent transition radiation produced by the relativistic electron bunches was focused by parabolic mirrors onto an optically active ZnTe crystal. The induced birefringence was sampled with ultrashort titanium sapphire laser pulses. The laser repetition frequency of 81 MHz was phase-locked to the 500 MHz radio frequency of the linac with a relative timing jitter of less than 40 fs. The measured bunch length amounts to 3.3 ps (FWHM) with an estimated resolution of 330 fs (rms).

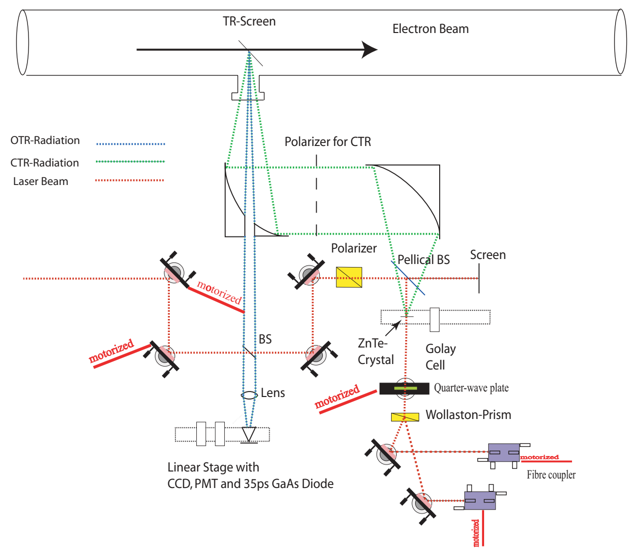

Figure 1: Schematic of the setup inside the linac area.

INTRODUCTION

Bunch length measurements in the 100 femtosecond regime are of high interest for VUV and X ray free electron lasers and for the planned femto-slicing experiments at the Swiss Light Source SLS and BESSY. The technique of electro-optic sampling (EOS) provides the possibility to measure the longitudinal charge distribution with very high resolution, determined by the width of the optical laser pulse and the relative time jitter between electron bunch and laser pulse. A 10-20 fs titanium-sapphire (Ti:Sa) laser is used to sample the birefringence which is induced in a nonlinear optical crystal by the co-moving electric field of a relativistic electron bunch or, alternatively, by the coherent transition radiation (CTR) generated by the bunch. The initial linear polarization of the laser pulse is converted into a slightly elliptical polarization which is then converted into an intensity modulation. By shifting the timing of the laser pulse relative to the bunch in sub-picosecond steps the time profile is obtained by sampling over many bunches. Previous accelerator-related EOS experiments have been carried out at the infrared free electron laser FELIX [Oep99], Fermilab, the TESLA Test Facility TTF [Bru03] and SLAC. Here we report on the successful continuation of our TTF experiments at the 100 MeV injection linac of the SLS.

EXPERIMENTAL SETUP

A schematic drawing of the experimental setup inside the tunnel of the SLS linac is shown in figure 1. Transition radiation is produced at a screen made from a 380 μm thick silicon waver with a 1 μm thick aluminum coating. Both optical and coherent transition radiation are coupled out of the beam pipe through a 60 mm diameter quartz window. The coherent transition radiation (CTR) is focused onto the ZnTe crystal by two parabolic copper mirrors with focal lengths of 200 mm. The optical transition radiation (OTR), having only a small divergence of $\approx \pm\frac{1}{\gamma} = \pm 10\,\mathrm{mrad}$, passes a 12 mm hole in the first mirror and is focused onto a photomultiplier which registers also the laser pulses and allows to adjust the temporal overlap of the Ti:Sa pulses and the electron bunches with sub-nanosecond precision.

The Ti:Sa laser has a pulse width of 15 fs, a central wavelength of 800 nm and a bandwidth of 65 nm. It is mounted on a vibration-damped optical table in the technical gallery of the SLS. The laser beam is guided into the linac bunker by a 15 m long optical transfer line equipped with five mirrors and two lenses ($f = 4$ m) which image the Ti:Sa laser onto the ZnTe crystal. The dispersion in the lenses stretches the laser pulses to about 120 fs FWHM. Since the expected length of the linac bunches is far longer, no attempt was made to compensate for the pulse lengthening by a pair of diffraction gratings. The beam transfer line has proven very stable, neither short-term nor long-term motions of the laser spot position inside the linac tunnel were observed.

A schematic view of the signal detection scheme is shown in figure 2. ZnTe is optically isotropic at vanishing field but acquires a birefringence in the presence of a strong electric field. The crystal is cut in the (110) plane with the the crystallographic (-1,1,0) axis oriented horizontally. Both the CTR and the Ti:Sa pulse are polarized horizontally. The induced birefringence can be described by a refractive index ellipse whose large axis is rotated by 45°

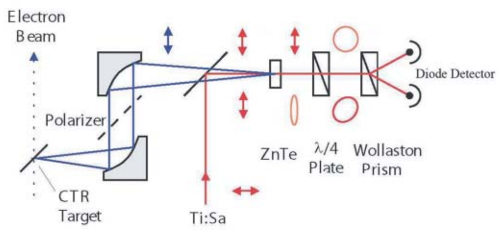

Figure 2: Simplified view of the signal detection using a quarter-wave plate, Wollaston prism and a balanced diode detector. The laser and CTR radiation are polarized horizontally, parallel to the (-1,1,0) axis of the TnTe crystal.

with respect to the horizontal axis. The laser polarisation components along the two main axes of the index ellipse acquire a phase shift difference when passing the crystal:

$$\Gamma \propto r_{41} E_{CTR}$$

where r_{41} is the electro-optic coefficient of ZnTe and E_{CTR} the electric field of the CTR pulse. Behind the ZnTe crystal the laser pulse is therefore elliptically polarized. The most sensitive method to measure this ellipticity is to pass the beam through a quarter wave plate, transforming the slight elliptic polarisation into a slightly perturbed circular polarisation, and then through a Wollaston prism, which serves for a spatial separation of the two orthogonal polarisation components. These are then coupled into optical multimode fibres and guided to a balanced diode detector located outside the linac tunnel. In the case of coincidence between CTR pulse and laser pulse the balanced detector signal is proportional to $\sin\Gamma$ and thereby roughly proportional to the electric field of the CTR pulse while without CTR the balanced detector signal will vanish.

SYNCHRONISATION

The EOS technique as a tool for ultra precise longitudinal bunch diagnostics depends critically on the precise synchronisation between the femtosecond laser pulses and the radio frequency (RF) of the linac. This proved to be a considerable challenge since the linac RF of 500 MHz has no subharmonics close to the 81 MHz repetition frequency of the Ti:Sa laser. Therefore a reference frequency of 3.5 GHz was chosen which is the 7^{th} harmonic of the linac RF and the 43^{rd} harmonic of the laser frequency. During the EOS measurements the linac gun trigger was derived from the Ti:Sa laser to ensure that each laser pulse coincides with a RF bucket position. The synchronisation unit is shown in figure 3. The repetition frequency of the laser is locked to the linac RF using a single-loop PLL (phase-locked-loop). A beam splitter directs the part of laser pulses to a 10 GHz photodiode. The 43^{rd} harmonic of the narrow photodiode signals is selected by a eighth-order bandpass filter, amplified and fed to the RF-port of a 3.5 GHz mixer. The 7^{th} harmonic of the linac RF is generated using an overdriven amplifier as a nonlinear device, filtered by a bandpass and

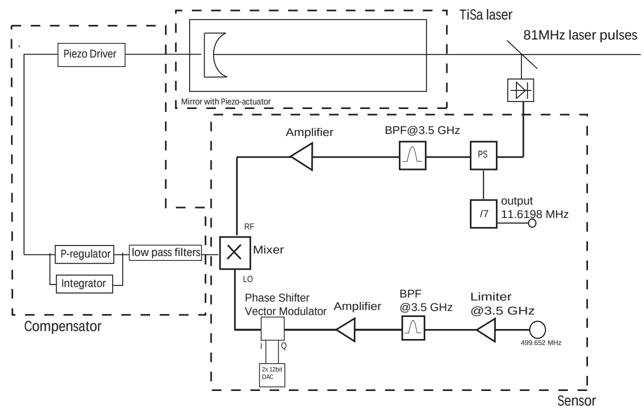

Figure 3: Schematic of the synchronisation unit.

fed to the LO-port of the mixer. The phase shift of the laser pulses with respect to the linac RF is accomplished by a vector modulator, shifting the phase of the 7^{th} harmonic of the linac RF in programmable steps. The error signal of the 3.5 GHz mixer is fed back to the piezo-controlled mirror of the laser resonator. The regulation of the laser repetition rate is accomplished via a PI controller.

A frequency analysis of the mixer error signal permits to determine the stability of the synchronisation circuit, see figure 4 (right). From the integrated spectral power density in the frequency range from 0.5 Hz up to 106.4 kHz we compute an rms time jitter of $\sigma_t = 35$ fs in the synchronisation. Not included is the relative jitter between the electron bunches and the linac RF.

DATA ANALYSIS AND RESULTS

Transfer function for coherent transition radiation. The CTR produced by the SLS linac bunches ranges from about 50 to 500 GHz. Diffraction has a strongly limiting effects on the transfer of this radiation to the ZnTe crystal. The optics code ZEMAX was used to compute the frequency-dependent transfer function of the radiation from the CTR screen to the ZnTe crystal. The finite radius of the CTR screen ($r = 23$ mm) and the aperture limitations provided by the vacuum window ($r = 30$ mm) and the parabolic mirrors (width and height of 130 mm) were taken into account.

The strongest diffraction limitation is given by the spot size of the Ti:Sa laser beam on the ZnTe crystal ($\sigma = 2$ mm). To compute the CTR transfer function, the two dimensional Gaussian laser spot has been convoluted with the intensity distribution of the CTR as predicted by ZEMAX. Simulations for various frequencies yield the transfer function shown in figure 4 (left). The small laser spot is responsible for the strong suppression of frequencies below 50 GHz.

Data acquisition. The linac was operated with 3.125 Hz bunch repetition frequency. After having established the coarse time overlap between the bunch arrival at the CTR

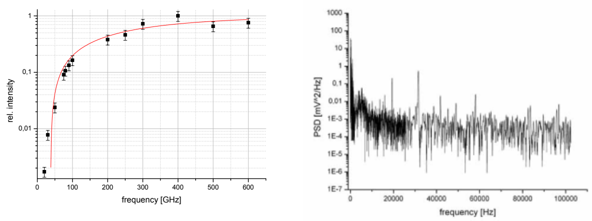

Figure 4: Left: Computed transfer function for CTR radiation from the CTR screen to the ZnTe crystal, convoluted with the laser beam profile at the crystal. The error bars represent the numerical uncertainties. Right: Noise spectrum of the error signal

screen and the Ti:Sa laser by means of the photomultiplier, a time interval of ± 500 ps was scanned in ps steps to find a coincidence signal in the balanced detector. This turned out to be straightforward. Once this signal was found, a narrow interval was scanned in 200 fs steps. At each time step the photomultiplier signal as well as the balanced detector signal for 10 consecutive bunches were recorded by a 7 GHz digital oscilloscope and stored in the internal memory of the scope. The signal of the balanced detector is plotted in figure 5 (top). as a function of the time delay. One observes a peak of several ps width with undershoots at the front and rear end. The undershoots are caused by the suppression of the low frequency components of the CTR signal. **Determination of the longitudinal bunch profile**. The data analysis was done in the following way: Starting from an assumed shape of the bunch a Fourier transformation was made and the CTR transfer function (figure 4 (left)) applied. The resulting frequency spectrum was Fourier back-transformed and compared to the measured signal. A single Gaussian for the bunch shape turned out to be inadequate. With two Gaussians of different amplitude, position and width an acceptable reproduction of the measured time profile was obtained. The lowest χ^2 was found for an assumed bunch profile composed of three Gaussians, see figure 5 (bottom). The overall time resolution of this experiment can be estimated by measuring the amplitude fluctuation of the balanced detector signal when the laser pulse is put on the rising edge of the CTR pulse. The amplitude jitter is then dominated by the arrival time jitter of the electron bunches. Assuming a linear dependency between time and amplitude on the flank of the signal, we derive an overall timing jitter of $\sigma_t = 330$ fs over a time span of 5 minutes. Here all sources of time jitter are included.

CONCLUSION AND OUTLOOK

The electro-optic technique has been successfully applied for bunch length measurements at the SLS linac. The synchronisation accuracy of the 81 MHz laser repetition frequency to the 500 MHz linac RF was better than 40 fs. Further improvements appear possible by employing a digital control scheme. This is planned for the electro-optic

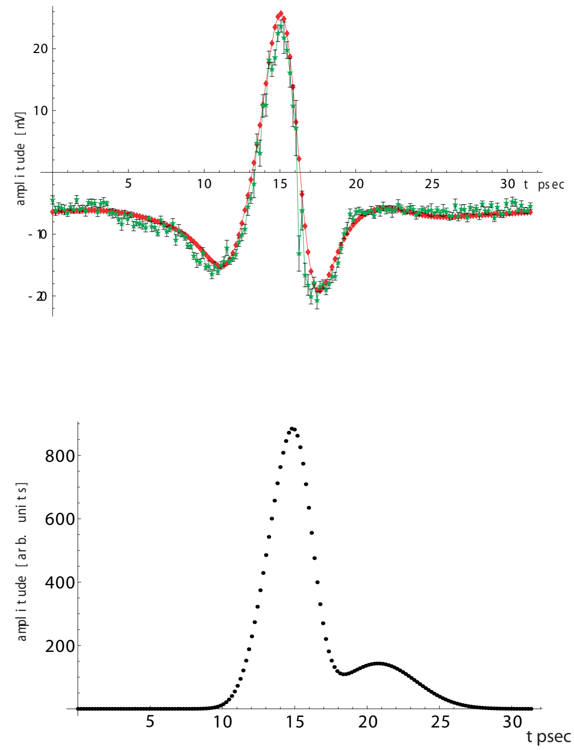

Figure 5: Top: The measured time profile of the CTR pulses (green with error bars) and the fit obtained with assumed bunch profile (below). Bottom: An assumed bunch profile composed of 3 Gaussians whose parameters are optimized to obtain the best fit of the measured profile (red curve in top plot).

sampling experiment at the DESY VUV FEL. Here the ZnTe crystal will be mounted inside the beam pipe of the linac to permit a direct measurement of the bunch field. This has the further advantage that the EOS measurements no longer need a transition radiation screen intercepting the electron beam. Hence longitudinal bunch diagnostics will be possible in parallel to FEL operation.

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