BUNCH LENGTH MEASUREMENTS AT THE SLS LINAC USING ELECTRO OPTICAL SAMPLING

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Abstract

An electro optical sampling experiment has been carried out at the 100 MeV electron linac of the Swiss Light Source (SLS). 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 minimum measured bunch length amounts to 3.0 ps (FWHM) with an estimated resolution of 300 fs (rms).

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 and BESSY. The technique of electro-optical sampling (EOS) provides the possibility to measure the longitudinal charge distribution with very high resolution, determined by the width of the optical laser pulse, the relative time jitter between electron bunch and laser pulse and the dispersion of the electric field pulse in the nonlinear optical crystal. A 15 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 [1], Fermilab, the TESLA Test Facility TTF [2] 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 wafer 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

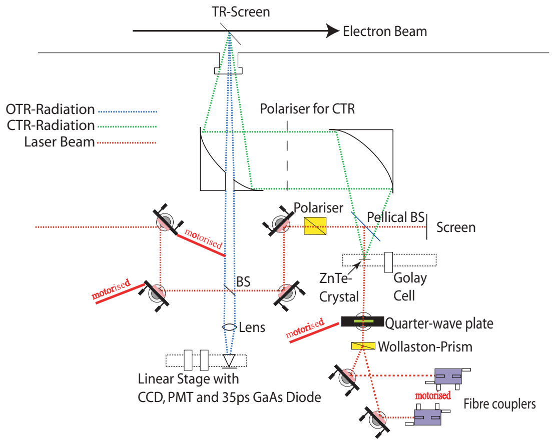

Figure 1: Scheme of the setup inside the linac area.

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. 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 simplified 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° with respect to the horizontal axis. The laser polarisation

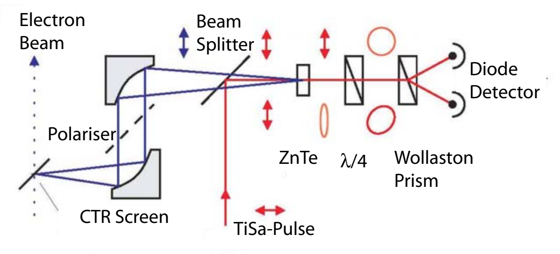

Figure 2: Simplified view of the signal detection using a quarter-wave plate, Wollaston prism and a balanced diode detector. The laser and CTR radiation are polarized horizontally, parallel to the (-1,1,0) axis of the ZnTe crystal.

components along the two main axes of the index ellipse acquire a phase shift difference when passing the crystal of $\Gamma \propto r_{41} E_{CTR}$ where r_{41} is the electro optical coefficient of ZnTe and E_{CTR} the electric field of the CTR pulse. Behind the ZnTe crystal the laser pulse will then be 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 fibers 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.

The EOS technique as a tool for ultra precise longitudinal bunch diagnostics depends critically on the 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. The synchronisation scheme is described in [3, 4].

An rms time jitter of $\sigma_t = 35$ fs was reached in the synchronisation. However, this does not include 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 up to 500 GHz. Diffraction has strongly limiting effects on the transfer of this radiation to the ZnTe crystal. The optics code ZEMAX was used to compute the frequency-dependent transmission 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 ($r \approx 130$ mm) were taken into account. The finite laser spot size ($\sigma = 2$ mm) is responsible for the strong suppression of frequencies below 50 GHz. The spatial intensity distribution of the laser pulse and the CTR electric field ($f = 100$ GHz) on the ZnTe crystal is shown in figure 3. The center of the ZnTe has been moved to a position where a movable Golay cell has registered the maximum signal.

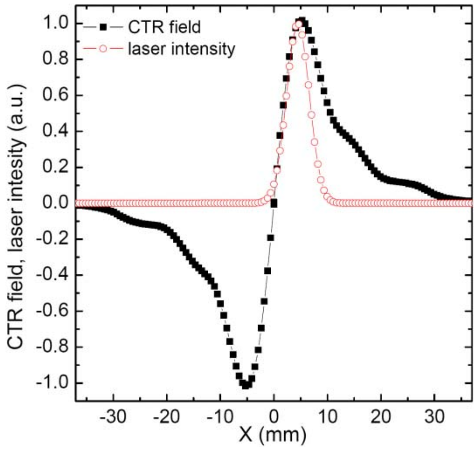

Figure 3: CTR electric field distribution at the crystal for 100 GHz. The center of the crystal, and so the laser spot, has been shifted to the position where a movable Golay cell has registered the maximum signal.

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 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 first EO-signal seen is shown in figure 4. 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 due to the suppression of the low frequency components of the CTR signal.

Determination of the longitudinal bunch profile

Starting from an assumed shape of the bunch a Fourier transformation was made and the CTR transfer function applied. The resulting frequency spectrum was Fourier back-transformed and compared to the measured signal. A sin-

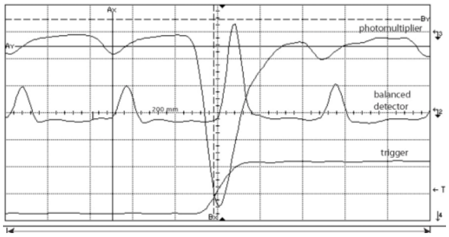

Figure 4: Oscilloscope screenshot with electro-optic signal. Top trace: Signal of the timing photomultiplier with laser pulses; Center trace: Signal of the balanced diode detector; Bottom trace: Linac trigger

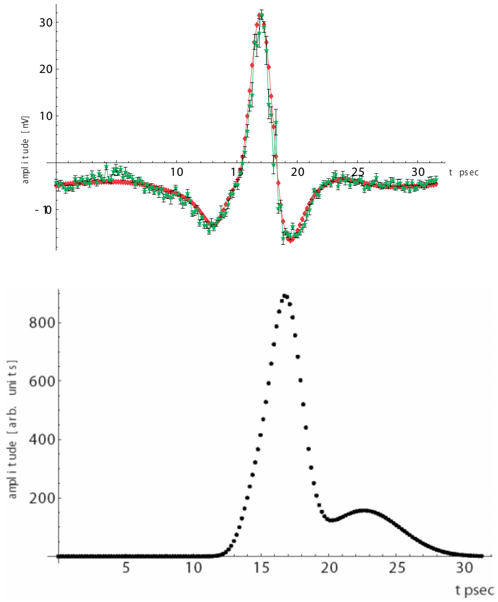

Figure 5: Top: The measured time profile of the CTR pulse (green with error bars) and the fit obtained with bunch profile composed of three Gaussians (see below). Bottom: Assumed bunch profile composed of three Gaussians whose parameters are optimized to obtain the best fit of the measured profile (red curve in the upper plot).

gle Gaussian for the bunch shape turned out to be inadequate. The best fit was found for an assumed bunch profile composed of three Gaussians of different amplitude, position and width, see figure 5 (bottom). At optimum bunch compression the FWHM of the electron bunch is 3.0 ps. 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 dependence between time and amplitude on the flank of the signal, we derive an overall timing jit-

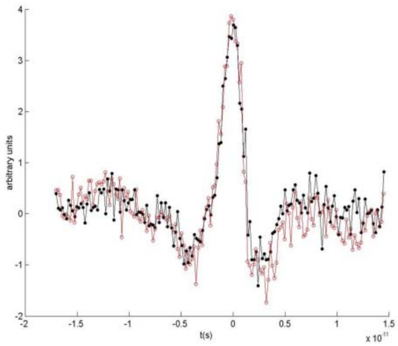

Figure 6: Two measurements taken directly after one another with positive and negative phase steps respectively.

ter of $\sigma_t = 300$ fs over a time span of 5 minutes. Here all sources of time jitter are included. The reproducibility was tested by two consecutive measurements with positive and negative time steps but otherwise identical parameters (figure 6). No significant difference between the measurements was seen, suggesting a high reproducibility over the time of 9 minutes needed to take the two measurements.

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 optical 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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