JITTER MEASUREMENT BY SPATIAL ELECTRO-OPTICAL SAMPLING AT THE FLASH FREE ELECTRON LASER

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Abstract

For pump-probe experiments carried out at the free electron laser FLASH (former VUV-FEL) at DESY, optical laser pulses generated by a titanium-sapphire (Ti:Sa) oscillator are synchronized with high precision to the vacuum ultraviolet FEL laser pulses. To measure the relative timing variations between the FEL and the optical laser pulses, a diagnostic tool to determine the electron beam arrival time at the undulator was installed. Here, the electron beam profile is spatially encoded in the laser pulse and read out by an intensified camera. The resulting single-shot timing signal has a minimum width of 150 fs (FWHM). The setup is ready to support pump-probe experiments.

INTRODUCTION

To get insight into fast physical processes in the fs-regime, pump-probe experiments are used. Two ultrashort pulses are overlapped temporally and spatially. While the first pulse induces a reaction and the second pulse probes the result of the first pulse. By altering the delay between both, the temporal evolution of the system can be measured. At the FLASH facility two color pump-probe experiments are carried out. One pulse is in the vacuum ultraviolet range generated by the FEL. The other pulse is generated by an amplified Ti:Sa oscillator at 800 nm. Both sources operate in burst mode, i.e. they emit a train of 800 pulses with a rate of 1 MHz every 200 ms. The Ti:Sa pulse is amplified by an optical parametric amplifier up to 20 μJ. At the experimental site it has a pulse duration of 120 fs (FWHM), thus producing an intensity in the range of $10\,\mathrm{TW}\cdot\mathrm{cm}^{-2}$ in the focus. Because the sources of the two pulses are independent, they have to be synchronized. The temporal resolution of the pump-probe experiments is limited by intrinsic jitter of FLASH and the optical laser system, which currently can not be compensated. The jitter is of the order of 400 fs RMS during one hour. This jitter determines and limits the utmost temporal resolution of pump-probe experiments.

The basic idea is to measure the jitter between the optical laser and the VUV bunch of the FEL for each pump-probe event. This is achieved by the Timing by Electro Optical Sampling (TEO) diagnostic. The relative arrival time between one laser pulse of the Ti:Sa oscillator and the electron bunch inside the accelerator tunnel of the FEL is measured. The 100 fs electron bunch gives rise to a 50 fs VUV pulse (see [1]), thus by determining the precise arrival time of the electron bunch, the arrival of the VUV photon pulse is known as well. However, due to technical reasons, the laser system has been built in a laser lab at the end of the FEL linear accelerator in close vicinity to the pump probe experiments. Therefore it is necessary to transport the laser to the location of TEO in the accelerator tunnel, which is located 160 m away from the laser lab (see Fig. 2). Knowledge about the mechanical stability of the beamline of FLASH lets us assume, that the arrival time of the ultra-violet laser pulse of the FEL at the pump-probe experiment only differs from the timing measurement in the tunnel by a constant offset. However, this still has to be verified by a pump-probe experiment. After a pump-probe experiment was performed, one can sort the experimental data set according the timing measurement. With this timing information the temporal resolution of the pump-probe experiment is determined only by the precision of the jitter measurement.

It has to be noted, that this is a relative measurement, i.e. the source of the jitter is of no concern, especially a possible time jitter of the synchronization between the laser and the master oscillator frequency of the FEL is measured and would vanish from the pump-probe data after sorting. First results at SPPS have shown, that a sub 50 fs resolution with such a set-up is possible [2].

In future this timing measurement tool will be used to realize user pump-probe experiments with a temporal resolution of 50 fs and better at the FLASH facility.

EXPERIMENTAL SETUP

The TEO diagnostic physically bases upon the Pockels effect and the relativistic transformation of the electric field of a relativistic charged particle.

The electron bunch passes an electro-optical crystal in close vicinity ($\approx$1mm). Due to Lorentz transformation the longitudinal component of the electric field of the relativistic electron bunch is contracted. In the laboratory system the electric field only shows a transversal component, which is proportional to the charge and the distance from the electron bunch. The electric field induces a slight birefringence inside the crystal. Its amount is proportional to the linear electron bunch density distribution. During the presence of the electrons the initially linear polarization of the Ti:Sa laser pulse is rotated. To measure the time of arrival between the electron bunch and the laser pulse, one has to introduce an angle of incidence of 45 degrees

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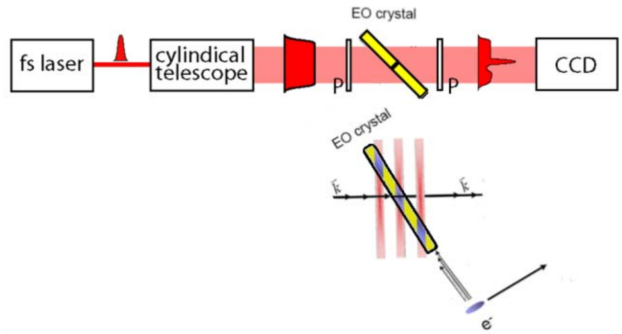

Figure 1: Simplified scheme of the EO spatial decoding. The laser and the field of the bunch are polarized horizontally, parallel to the (-1,1,0) axis of the GaP crystal. Due to the angle of incident of 45 degree, the position of the polarization variance inside the beam profile is depending on the relative arrival of the optical pulse and the electron bunch at the EO crystal.

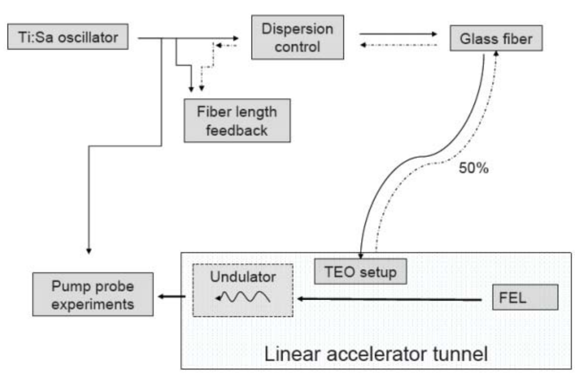

Figure 2: Scheme of the Timing by Electro-Optical Sampling (TEO) experiment.

between the laser and EO crystal surface. Only the intersection of the laser pulse with the EO crystal is affected by the polarization change. Now the relative arrival time is encoded spatially inside the beam profile as shown in Fig. 1 (Spatial Electro-Optical Encoding) and can be read out with an analyzator and a CCD camera.

As mentioned before, the optical laser pulse has to be transported to the TEO experiment by a polarization maintaining, single mode glass fiber of 160 m length. Thus, one has to compensate the dispersion of 160 m of bulk quartz crystal (SQ1) to have a short pulse at the EO crystal. Without dispersion control the pulse would spread to 350 ps. The dispersion control is performed by a grating compressor, which can compensate $6.1 * 10^6 fs^2$ of (normal) first order dispersion. However, this compressor introduces a negative amount of Third Order Dispersion (TOD) as well. Together with the glass fiber, the laser pulse accumulates $-1.5 * 10^7 fs^3$ of TOD. The liquid crystal phase modulator with 640 pixel is able to compensate up to $1.2 * 10^7 fs^3$ of Third Order and higher order dispersion. Thus, a little part

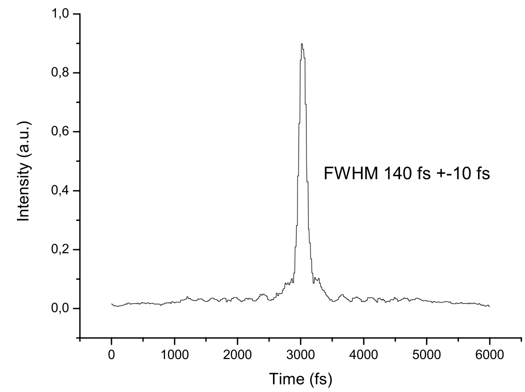

Figure 3: Autocorrelation of recompressed laser pulse at EO crystal. Assuming a Gaussian profile, duration of the laser pulse is 100 fs. The influence of the remaining TOD leads to small oscillations visible in the wings.

of TOD is left and its influence can be seen in the autocorrelation trace (Fig. 3). The algorithm to find the overall dispersive compensation function ϕ^- determines the maximum of the SHG intensity for every polynomial coefficient of the Taylor expanded phase function. With the maximal phase function ϕ^- max applied to the shaper matrix, we were able to recompress the bunch down to about 100 fs (FWHM) at the EO crystal. (see Fig. 3).

Due to thermal expansion of the glass fiber, long term drifts of the laser arrival time at the EO crystal occur. Its thermal expansion coefficient is $5 * 10^{-7} \cdot K^{-1}$, which gives rise to drifts in the ps-range. To compensate this length deviation, a fiber feedback system was installed. 50% of the laser intensity at the TEO site is reflected back into the glass fiber to the laser lab. There, a cross correlation is performed between the reflected pulse, which has only 3 pJ, with a pulse originated of the oscillator. The cross-correlation is scanned every 20 sec and provides the feedback signal. According to this feedback signal, the optical path length is modified, such that any deviation due to fiber elongation is compensated.(see Fig. 2).

MEASUREMENTS

The temporal resolution to measure the relative arrival time between the FEL electron bunch and the laser pulse is determined by the material and thickness of the electro-optical crystal. Furthermore, it is depending on the duration of the laser pulse at the site of the EO crystal $\tau_0 = 100 \pm 10$ fs, the pulse length of the electron bunch and of its energy. For our set of parameters the lower limit for the EO signal width for a 300 μm thick Zink-Tellurite (ZnTe) crystal was calculated to be $\approx 350\ fs$ (FWHM). The lower limit for a 180 μm thick GaP crystal was calculated to be $\approx 150\ fs$ (FWHM) [3].

This was reproduced by our experiments. The measured

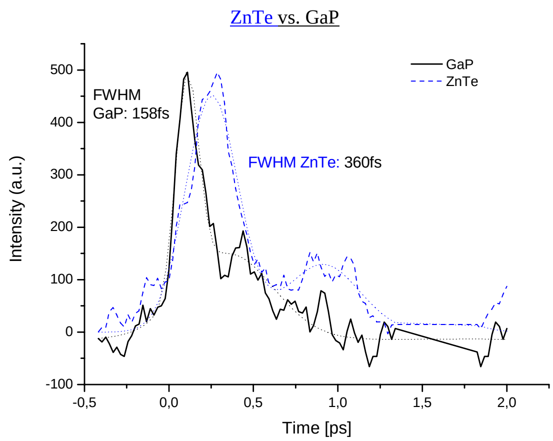

Figure 4: Comparison between the TEO signal with GaP and ZnTe crystal. The temporal position of relative arrival is given by the rising edge. The rise time of the GaP EO signal is 100 fs.

width of the TEO signal with GaP is 158 fs (FWHM) and with ZnTe is 360 fs (FWHM), which is visible in (see Fig. 4). The shape of the signal is proportional to the longitudinal electron density distribution. Thus, TEO is able to monitor online the longitudinal electron bunch shape in a non-invasive way. A deeper investigation into this kind of measurement is given in [4].
For the TEO diagnostic tools, the GaP-crystal is used. With this crystal the rise time of the EO signal is about 100 fs, thus much faster when compared to ZnTe (see Fig. 4). Therefore, the arrival time of the electron bunch with respect to the laser pulse can be determined with a precision of at least 50 fs by fitting the leading edge. A pump-probe measurement to proof this theory had been carried out, but data evaluation was still ongoing during the writing of this paper.

The macro bunch repetition rate of the FEL is 2 or 5 Hz and every macro bunch can consist of a burst of up to 800 micro bunches with a repetition rate of 1 MHz. In principle, TEO can detect the arrival time data of each micro bunch for every bunch train. However, at the moment TEO provides jitter data only for one selected micro bunch of each bunch train. The arrival time of the first micro bunch of each macro bunch for one hour of measurement time is shown in Fig. 5. The measurement shows slow and fast components of the jitter fluctuations. They add up to an overall jitter of 400 fs within 60 minutes. If the measurement is performed for only 10 minutes, the RMS jitter is reduced to ≈200 fs, because long term drifts are not accounted any more. Thus, it is important to mention the time base together with a RMS jitter value to make them comparable.

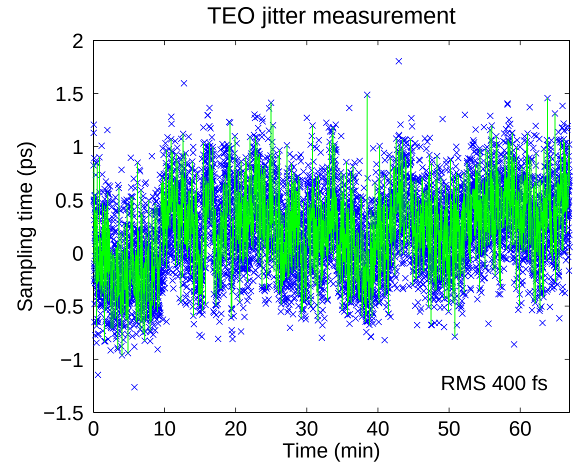

Figure 5: Measurement of the relative arrival time jitter over 60 minutes (data points with interpolated spline function). The RMS jitter is 400 fs.

CONCLUSION

The Electro-Optical Spatial Decoding technique offers the opportunity of an online non-destructive single-shot measurement of the relative arrival time between the pump laser and the electron bunch (respectively VUV pulse) with a resolution of better than 50 fs. Furthermore it is able to monitor the longitudinal electron density distribution of the electron bunch with a resolution of ≈ 150 fs.

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