

PROPOSAL FOR A SUB-100 fs ELECTRON BUNCH ARRIVAL-TIME MONITOR FOR THE VUV-FEL AT DESY

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Abstract

For pump-probe experiments at the VUV-Free Electron Laser (FEL) at DESY, an external optical laser system will be installed, capable of delivering ultra-short pulses of high intensity. The laser pulses with a central wavelength of 800 nm are correlated with the VUV-FEL beam which operates in the wavelength regime between 6 nm and 80 nm. The expected duration of the FEL pulses is in the 100 fs range. For pump-probe experiments a precise timing of the FEL and Ti:Sa pulses is mandatory. In this paper we describe the layout of a high-resolution electron bunch arrival time monitor based on an electro-optic technique. We present numerical simulations for a specifically designed optical system that allows the transport of an ultra-short laser pulse through a 170 m long optical fibre without pulse stretching. Furthermore, the electro-optical effect in a non-linear crystal is simulated for various thicknesses of the crystal.

INTRODUCTION

The VUV-FEL at DESY consists of a superconducting linear accelerator that drives a SASE-based FEL. The high brightness beam is produced in an RF photo-injector. The high peak current of 2.5 kA required for FEL operation is achieved by stages of longitudinal bunch compression, combining off-crest acceleration to produce an energy-chirp in the bunches with an energy-dependent path length in a magnetic chicane. The first compression from 20 ps to 2 ps (FWHM) takes place at an energy of 100 MeV, the second one from 2 ps to 0.5 ps (FWHM) at 450 MeV. Two more acceleration modules rise the energy to 850 MeV. The FEL beam is produced in a 30 m long undulator and transported over a distance of 50 m to the experimental hall which houses also the pump-probe laser system. Further details on the layout can be found in [1].

Gradient and phase jitter in the superconducting cavities upstream of the magnetic chicanes cause a jitter in the arrival time of the electron bunches at the undulator. Thus an ultra-precise monitor, capable of measuring the relative synchronisation of the electron bunches and the Ti:SA pulses on a bunch-by-bunch basis, appears highly desirable.

The method proposed is one that has been successfully tested at the Sub-Picosecond Pulse Source (SPPS) [2]. It

contains:

- a laser transport to the accelerator through a 170 m long single-mode fibre with optical path length stabilisation [3], and
- a single-shot electro-optical (EO) measurement of the electron bunch timing using a spatial correlation technique.

LAYOUT OF THE EXPERIMENT

Electro-optical technique. The induced birefringence in an electro-optical crystal such as ZnTe, which is caused by the electric field of a relativistic electron bunch, transforms the temporal bunch profile into different phase retardations of the two polarisation components of the laser. By means of a quarter wave plate and a Wollaston prism, the resulting elliptic polarisation is transformed to an amplitude modulation which is detected by photo-diodes or cameras. The crystal is placed at an adjustable distance of several mm from the electron beam. The laser beam crosses the crystal at an angle of 45°, whereby the time profile of the electron bunch is encoded into the transverse intensity distribution of the laser light. The crystal has a wedge shape which allows to vary its thickness by shifting the laser spot horizontally (see Fig. 1).

Laser system. The pump-probe laser system comprises a Ti:Sa pulse train oscillator (KMLab MTS mini Ti:Sa) and an optical parametric amplifier (OPA) pumped by a Nd:YLF laser in burst pulse mode (1 MHz for 800 μ s) to be compatible with the electron bunch repetition frequency of 1 MHz. The Ti:Sa oscillator repetition rate is 108 MHz, the central wave length is 800 nm, the bandwidth of 30 nm. The laser pulses are Fourier limited with a pulse duration of 30 fs FWHM. To reduce background at the experiment by leakage through the OPA crystal the laser pulses are gated with a Pockels cell triggered with 1 MHz.

Laser transport. The EO-technique requires an ultra-short laser pulse and a well-defined polarization at the EO-crystal. To avoid an expensive laser beam transport line, a polarization preserving single-mode fibre (FS-LS-4616, Thorlabs, material SQ1) with a core diameter of 5.3 μ m and a length of 170 m is used [3]. The linear dispersion in the fibre would increase the pulse length to almost 400 ps, long wavelengths being at the front of the pulse and short ones

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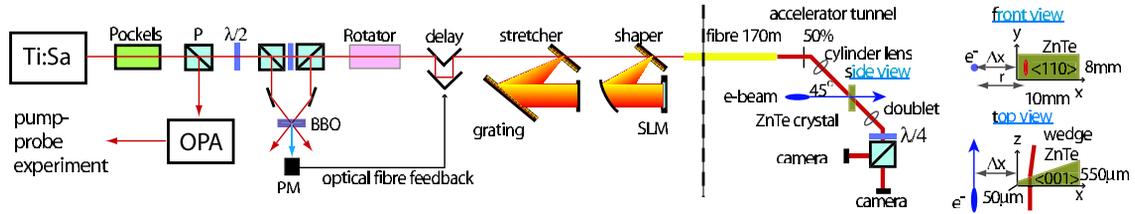


Figure 1: Scheme of laser pulse propagation

at the tail. This effect is compensated by a pair of gratings (1500 lines/mm) in front of the fibre which stretch the laser beam to about 400 ps but with an inverted arrangement of the wavelengths. This pulse will then be compressed by the fibre. The remaining non-linear dispersion is removed using a Spatial Light Modulator (SLM), placed in the focus of a high precision cylindrical mirror. The optical path length of the fibre is actively stabilized. A beam splitter reflects 50% of the laser beam back into the fibre for cross-correlation with trailing laser pulses. The overall round trip time amounts to 1.6 μ s. The cross-correlator signal is monitored by a photomultiplier which controls a motor driven optical delay stage. To optimize the configuration the laser transport chain of single mode fibre, grating stretcher and SLM has been investigated with the code Lab2 [4]. The result of the simulation is shown in Fig. 2.

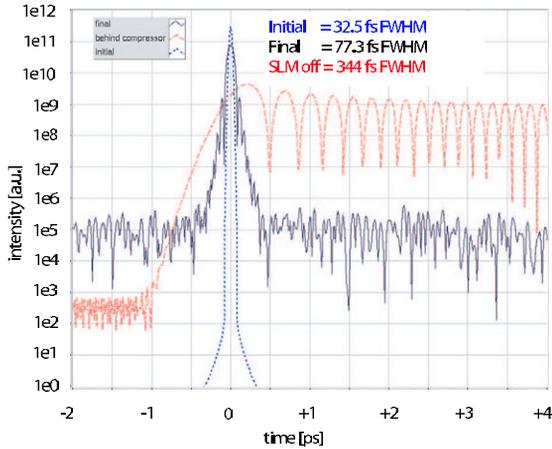


Figure 2: Simulated time distribution of laser pulse at the EOS experiment. Blue: original laser pulse, red: pulse behind fibre without spatial light modulator (SLM), black: pulse shape with SLM.

Imaging system. The laser beam is focused with a cylindrical lens onto the ZnTe crystal resulting in a 0.1 mm \times 2 mm FWHM laser spot. The crystal is imaged with an optical telescope onto the detectors for the two polarization components providing a magnification by a factor of two. The design has been optimized using the optics simulation code ZEMAX. The tilt of the crystal with respect to the optical axis is taken into account by a corresponding tilt of the detectors. The expected resolution is 5 μ m, close to the diffraction limit of the optics.

The initial laser polarization is linear. In the crystal the

laser beam acquires a slight elliptic polarization. A $\lambda/4$ plate turns this into a slightly perturbed circular polarization. A Wollaston prism separates the two orthogonal polarization components which are then measured by two detectors. Both polarization states carry the full information, one being increased and the other one decreased by the electro-optic effect.

Readout system The coarse timing between the Ti:Sa laser and the electron bunches will be established by detecting the laser pulses and the optical transition radiation (OTR) of the electron bunches with a fast photo diode. The relative timing can be adjusted with a precision of about 100 ps. Two different detectors are foreseen for measuring the polarization change of the laser beam: an intensified CCD camera and a gated CMOS detector array consisting of 1024 photo diodes arranged in a line, which can be gated down to 20 ns. The smallest gate width of the camera is 5 ns. Both polarizations can be brought onto different areas of the CCD chip. A new camera with a CMOS detector array is under development.

SIMULATION OF THE EO-TRANSFER FUNCTION

In a dc electric field the relative phase retardation of the laser polarization components along the principle axes of the crystal is

$$\Gamma = \frac{2\pi}{\lambda_0} \cdot d \cdot n_0^3 \cdot r_{41,dc} \cdot E_{dc}, \quad (1)$$

Here d denotes the crystal thickness, λ_0 the central wave length, n_0 the index of refraction at λ_0 , and $r_{41,dc}$ the dc electro-optical coefficient.

The Fourier spectrum of a sub-picosecond bunch with a normalised longitudinal charge distribution $\lambda(t)$

$$E_r(\omega) = \frac{Z_0 Q}{2\pi r} \cdot \frac{1}{2\pi} \int \lambda(z/c - t) e^{i\omega t} dt \quad (2)$$

extends far into the THz regime. Therefore, the frequency dependencies of the refractive index $n(\omega)$ and the electro-optical index $r_{41}(\omega)$ have to be taken into account as well as the slippage between the group velocity c/n_g of the laser pulse and the phase velocity c/n of the THz field. Following the approach in [5] the phase retardation Γ depends on the laser pulse delay τ in the form

$$\Gamma(\tau) = \frac{2\pi}{\lambda_0} \cdot n_0^3 \cdot d \int_{-\infty}^{\infty} r_{41}(\omega) G(\omega) E_r(\omega) e^{-i\omega\tau} d\omega \quad (3)$$

with the EO-response function

$$G(\omega) = \frac{2}{1+n} \cdot \frac{e^{i\omega/c(n-n_g)d} - 1}{i\omega/c(n-n_g)d}. \quad (4)$$

For ZnTe the refraction index and the electro-optic coefficient can be described as [6]

$$n(\omega) = \sqrt{1 + \epsilon_\infty \frac{\omega_{LO}^2 - \omega_{TO}^2}{\omega_{TO}^2 - \omega^2 - i\gamma\omega}} \quad (5)$$

$$r_{41}(\omega) = r_{41,dc} \left(1 + \frac{C\omega_{TO}^2}{\omega_{TO}^2 - \omega^2 + i\gamma\omega} \right). \quad (6)$$

The values of the longitudinal and transverse optical phonon resonance frequencies ω_{LO} and ω_{TO} , the lattice damping γ and the coefficient C are listed in Tab. 1. For thin crystals the Fabry-Perot interference at the front and back surface has to be taken into account yielding [2]

$$G_{FP}(\omega) = \frac{(1-r)}{1-r^2 e^{i\omega/cnd}} \left(\frac{e^{i\omega/c(n-n_g)d} - 1}{i\omega/c(n-n_g)d} + e^{+ind\omega/c} \frac{e^{-i\omega/c(n+n_g)d} - 1}{i\omega/c(n+n_g)d} \right). \quad (7)$$

The phase retardation $\Gamma(\tau)$ is plotted in Fig. 3 for a $100\mu\text{m}$ ZnTe crystal.

Table 1: Optical coefficients of ZnTe [6],[7].

	f_{TO} [THz]	f_{LO} [THz]	$\gamma/2\pi$ [GHz]	ϵ_∞	C	$r_{41,dc}$ [pm/V]
ZnTe	5.3	6.18	90.2	6.7	-0.07	4.0

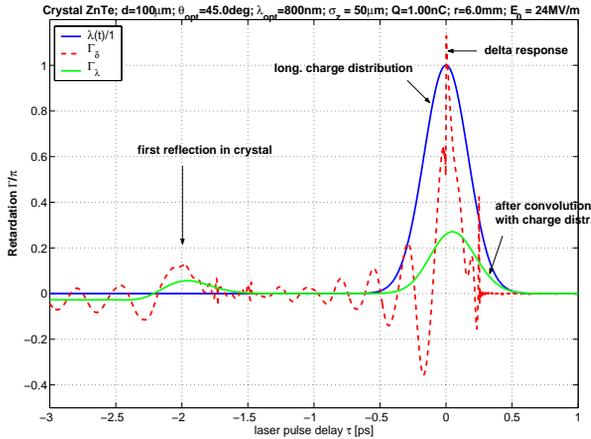


Figure 3: Phase retardation Γ of a laser pulse having passed a $100\mu\text{m}$ thick ZnTe crystal. The red curve shows the EO-response for a delta function like charge distribution. The sharp transitions are not visible for electron bunches with $50\mu\text{m}$ RMS length (green).

Finally, the laser intensity observed in the detectors is given by

$$\frac{I_{S,P}(\tau)}{I_0} = \frac{1}{2} \left(1 \pm \frac{1}{I_0} \int_{-\infty}^{\infty} I(t) \sin(\Gamma(t - \tau)) dt \right) \quad (8)$$

with S and P the two laser polarisations, $I(t)$ the intensity profile, and I_0 the total pulse energy. For a horizontal distance of 5 mm of the electron beam to the edge of the wedge-shaped crystal, the expected signal in a balanced detector, $(I_S - I_P)/I_0$ is plotted in Fig. 4 as a function of the horizontal laser position and time.

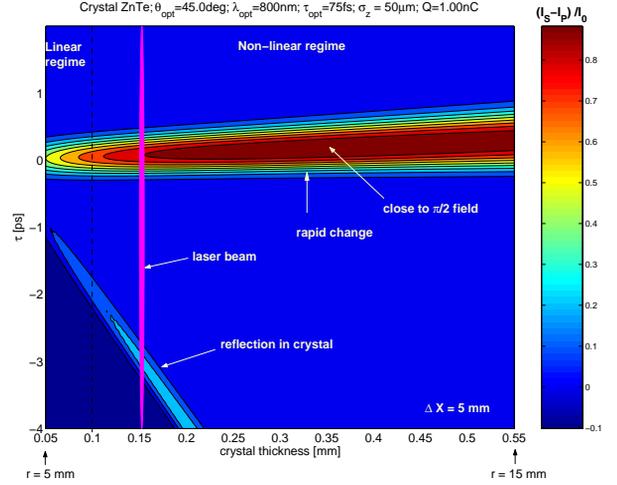


Figure 4: Simulation of contrast ratio in a balanced detector array across a wedge-shaped ZnTe crystal. The simulation takes into account the finite duration of the laser pulse and the limited optical resolution of the vertical laser diffraction pattern.

is located close to the edge of the crystal the bunch distribution can be measured. Towards larger crystal thickness, the phase retardation exceeds $\pi/2$. Nevertheless, the sharp rising edge permits a precise determination of the beam arrival time.

SUMMARY

In this paper, a single-shot longitudinal electron bunch profile and timing monitor is described. A relative timing jitter between electron bunch and femtolaser pulse of less than 50 fs (FWHM) appears feasible.

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