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Table of Contents:

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Abstract

Understanding dynamics on ultrafast timescales enables new and unique insights into important processes in materials and life sciences. In this respect, the fundamental pump-probe approach based on ultra-short photon pulses aims at the creation of stroboscopic movies. Performing such experiments at the European XFEL or the ELI facilities allows an enormous widening of the accessible parameter space for the excitation and/or probing light pulses. Compared to table-top devices, critical issues of this type of experiment are the fluctuations of the timing between the accelerator-based source and external laser systems. This can be overcome by measuring the arrival time of every photon pulse. The main challenge, but also the opportunity, of a facility like the European XFEL lies in its much higher duty cycle. Since the accelerator is based on superconducting radio-frequency (SRF) technology, operation at repetition rates in the macro pulse burst of 4.5 MHz is feasible, providing individual experiments with up to 27000 X-ray pulses per second. One approach, pursued within the PUCCA work package, is the measurement of the arrival time of the X-ray pulses directly at the experiment by means of a cross correlation in a liquid jet (Task 7.1.2: liquid-jet based arrival time monitor, see also Deliverable D7.2.). An alternative approach is based on the observation that the arrival time of a secondary radiation pulse from an electron accelerator can be deduced by means of single shot electro-optic sampling measurement of residually radiated single-cycle THz pulses in the far-field [TAV11]. As could be shown, the achievable time-resolution between an X-ray pulse and a superradiant THz pulse generated by 2 independent sources and transported over several 10s of metres can still be in the sub 10 fs regime [FRU09]. The advantage of this indirect way to determine the arrival time of the X-ray pulses lies (i) in the fact that the method is fully non-invasive to the X-ray pulses as any interaction in the monitor can be avoided and (ii) in the enormous sensitivity of the electro-optic detection of THz pulses which allows operation down to charges in the sub pC regime. The interaction of the THz pulses with matter, and in this specific case the electro-optic crystal, is much weaker than X-ray-matter interaction. Accordingly the problematic of the high repetition-rate encountered and dealt with in Task 7.1.2 in utilizing a liquid jet is here completely avoided. A drawback is that the location of such a monitor at the European XFEL would have to be close to the electron beam dump which is more than 500 metres from the experimental station. Achieving sub 10 fs time-resolution thereby will not be possible. Since the generation of the THz pulses acting as time-prompt required relativistic electron bunches of durations in the ps regime or below the method cannot readily be transferred to all-laser based facilities.

In this report the following questions are addressed: (i) limits in bunch charge/THz pulse energy to infer whether the monitor would be usable also in the low-charge mode of operation of XFELs, (ii) limits for the maximal possible repetition-rate, (iii) limits in time resolution, (iv) reliability and achievable dynamic range in benchmark pump probe experiments.

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1. Introduction

Arrival time monitoring and the subsequent correction of the derived data is in principle an established technique at X-FELs where arrival time and intensity binning is meanwhile performed routinely [CAV05,AZI09,TIE09,BIO14]. However, there is an obvious reason why a further development of this conceptual approach is still necessary. XFEL facilities have so far operated at comparatively low repetition rates/duty cycle between 120 Hz [EMM10] and 1 MHz/8000 pulses per second [TIE09]. The European XFEL will operate with a micro pulse repetition rate of up to 4.5 MHz yielding up to 27000 pulses per second. At such high repetition rate existing concepts fail to work, either (i) because of damage thresholds or long lived excited states in materials utilized for laser-X-ray cross correlation and/or (ii) because the underlying techniques are not able to sample at 4.5 MHz rates. In this report we present the evaluation of an arrival time monitor that is based on determining the arrival time of the X-ray pulses indirectly from far-field THz pulses, which are emitted by the short electron bunches in the European XFEL accelerator after the X-ray undulator section. The main advantage of this scheme is the fact that sample damage due to X-rays is completely avoided. Moreover the single-shot detection of far-field THz pulses has been proven to be very sensitive. This may allow timing measurements at very low bunch charges required for single-mode operation of European XFEL.
The report is organized as follows. Below we describe the TELBE facility which is serving as the test field for the THz timing tool to be developed in EUCALL, we then present the status of the ***objective*** to develop a demonstrator THz timing tool for the European XFEL and thereafter present the ***results of our benchmarking experiments*** with the existing prototype monitor: (i) bunch charge limits, (ii) repetition rate limits, (iii) time resolution limits and (iv) reliability/operational experiences.

TELBE – a test facility for electron bunch diagnostics at quasi-cw SRF accelerator beams
The tests shown in this report have been performed with a first prototype monitor at the TELBE facility [GRE16] driven by the quasi-cw SRF accelerator ELBE which allows quasi-cw operation up to repetition rates of 13 MHz but can also be run in macro pulse mode (see Figure 1). Bunch charges can be varied between few pC and 100 pC.

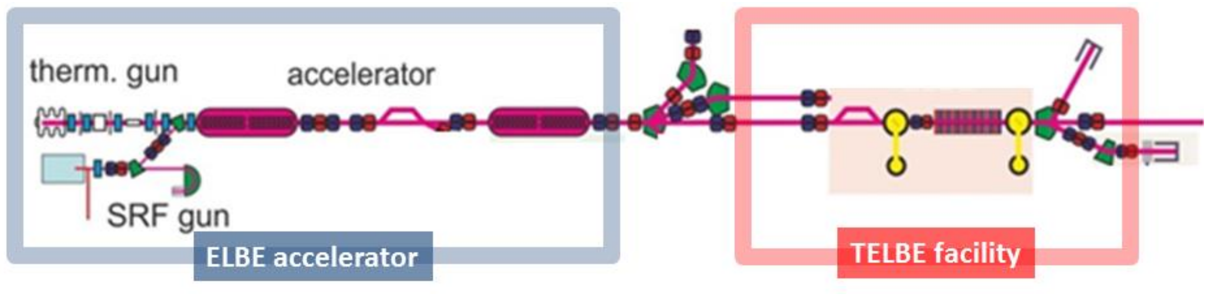

Figure 1: ELBE accelerator (left) and TELBE facility (right). TELBE serves as a test facility for quasi-cw electron beams in the HGF program topic: accelerator research and development.

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ELBE is a low energy electron accelerator allowing acceleration of electrons up to merely 40 MeV [GAB00]. However the effect of lower beam energy in the few 10 MeV range on the emitted THz pulse energy is well known and can be taken into account. Far-field THz pulses are emitted at two types of radiators, a diffraction radiation screen and an undulator (see Figure 2), and are transported by optical beamlines into the TELBE laboratory (see Figure 3). Thereby TELBE is one of few places in the world where a THz-based arrival time monitor can be tested at the appropriate repetition rate and in an ultra-fast laboratory environment.

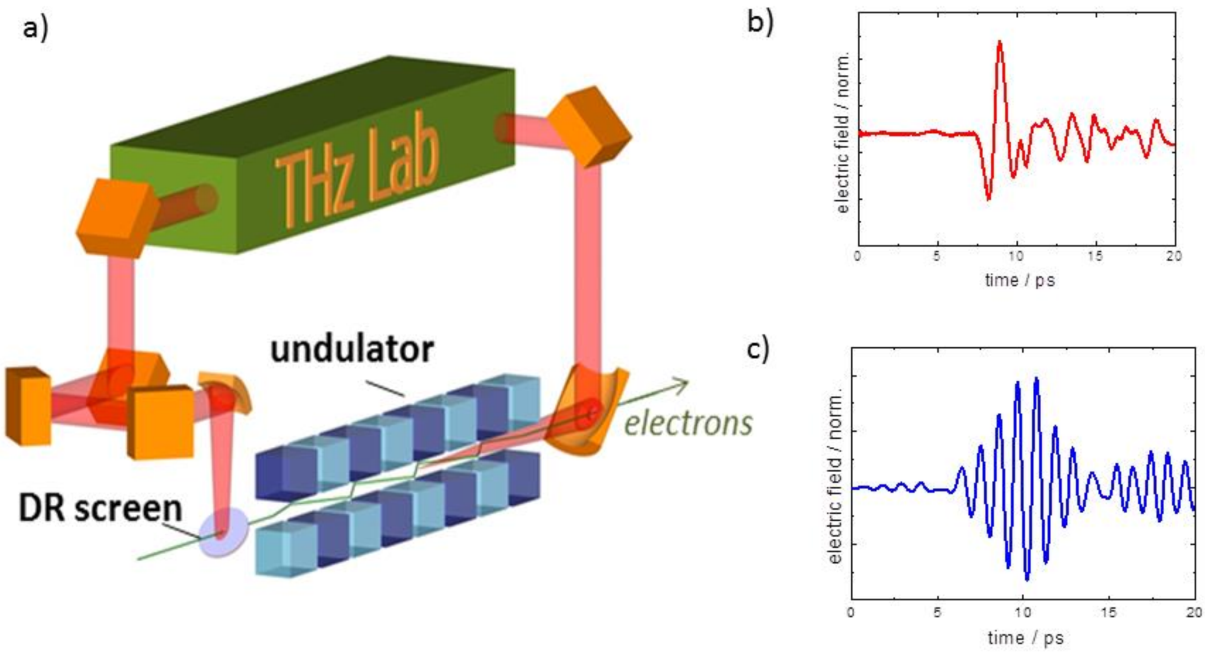

Figure 2: a) Arrangements of the THz emitters in the electron beamline. b) THz waveform emitted by the diffraction radiator. These pulses act in the following as time prompt. c) THz waveform emitted by the undulator. These pulses are in the following used in benchmark pump-probe experiments and are the equivalent of the X-ray pulses.

The laboratory is equipped with 2 different fs laser systems. One system is a laser-amplifier of the type: Coherent Reg A 9000 which provides µJ pulse energies at 800 nm wavelength at up to 300 kHz repetition rate, the second fs laser system is of the type Coherent Legend and provides few mJ pulse energies at a repetition rate of 1 kHz also at 800 nm wavelength. Both laser systems can be locked to the accelerator masterclock via RF locking or via the fibre link locking of the XFEL type.

2. Objectives

The objective for the THz timing tool is to build a demonstrator device that is tested and benchmarked at the ELBE accelerator at the HZDR. The eventual device shall work at a repetition rate of up to 4.5 MHz macro pulse. The arrival time for a photon pulse from one synchrotron radiator which is used in real-world ultra-fast experiments is determined indirectly by means of a single-cycle THz pulse emitted the same electron bunch but from another second radiator in the same electron accelerator. In the following the current progress is described.

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2.1. (far-field) THz based arrival time-monitors

The original concept for an arrival time monitor for X-ray FEL based on the indirect clocking of far-field THz pulses has been first demonstrated at FLASH in 2008. The FLASH XUV FEL allows transport of far-field THz radiation from the accelerator tunnel into the experimental hall over a distance of > 60 m and to combine these THz pulses with XUV pulses emitted from the same electron bunch [GEN08]. The crucial first experiment was a “cross correlation” based on THz streaking of photoelectrons generated in Krypton [FRU09] which established that THz and XUV pulses have an intrinsic synchronization of better than 10 fs (FWHM) despite two independent optical beam paths of > 60 metres each. The second experiment verified that THz pulses residually generated at the XUV undulator exit can be easily measured by single-shot electro-optic sampling and can hence serve as a time prompt for the XUV arrival time [TAV11]. The scheme based on temporal-decoding is shown in Figure 4.

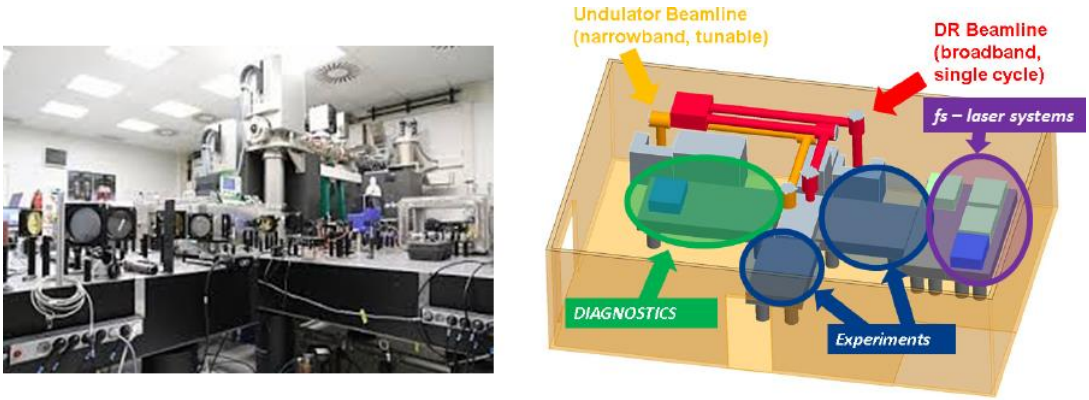

Figure 3: TELBE laboratory used for the benchmarking of the first prototype set-up presented in this report

The temporal decoding scheme [TIL07] in combination with the available probe laser systems limit the maximal repetition rate of this monitor to 10 Hz.

2.2. Single shot electro-optic sampling techniques – design considerations

The arrival time measurement is based on single-shot electro-optic sampling. A variety of techniques have been developed over the past years that fundamentally work by mapping the timing information encoded on a sufficiently stretched near infrared laser pulse into a spatial coordinate. For the THz timing tool demonstrator developed for the European XFEL two of these techniques were considered. Temporal decoding, where the time-to-space mapping is achieved by difference frequency mixing between the stretched pulse with the encoded THz field and a short probe pulse, as shown in Figure 4 and described in detail in [TAV11]. This technique has the disadvantage that the frequency mixing requires pulse energies in the probe laser beyond the few 10 µJ regime. It also requires a sensitive ICCD camera for imaging the relatively weak DFG signal. Thereby the demands on the laser system used for the timing are considerable in the combination of pulse energy and 4.5 MHz repetition rate. The developed pump probe laser system at European XFEL [LED16] however would fulfil these requirements, although a considerable part of the pulse energy would

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then be lost for the actual pump probe experiment. However, the camera utilized for imaging in temporal decoding is another drawback. Commercially available ICCD cameras, as required to observe the SHG pulses, are still only available at low repetition rates. For these reasons it was decided that temporal decoding at this point is not the ideal technique for a high-repetition-rate source such as the European XFEL.

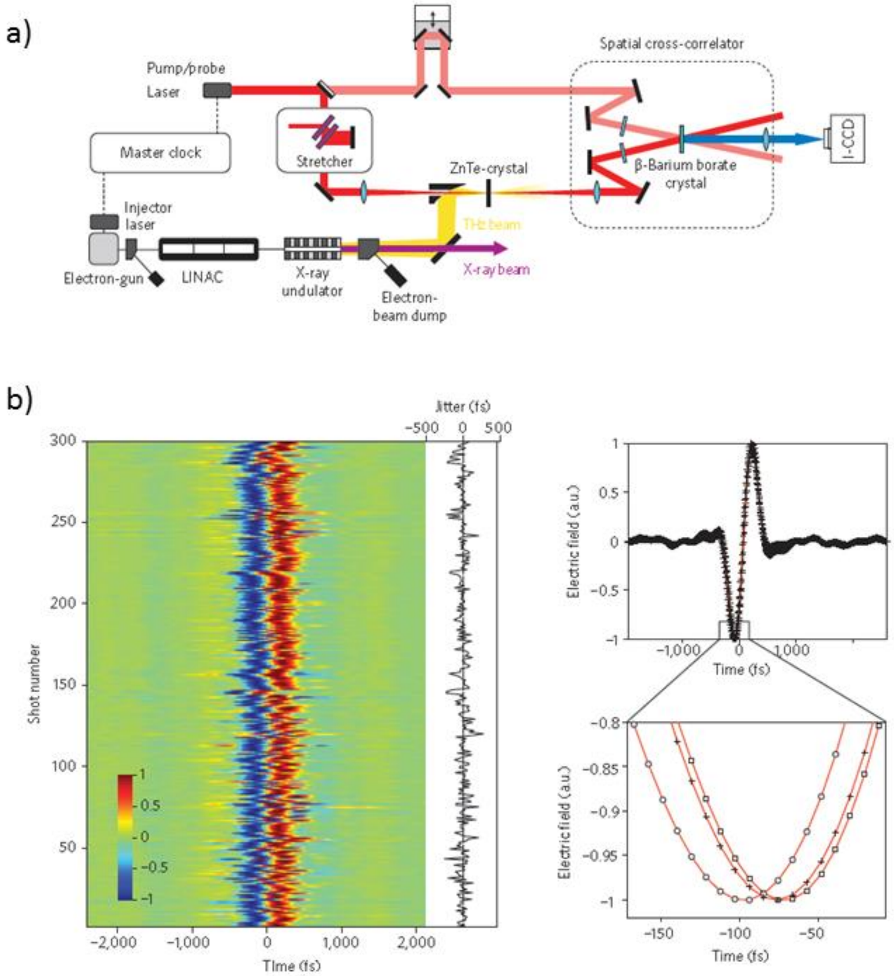

Figure 4: THz timing tool at the FLASH FEL. a) scheme and b) arrival time measurements proving the achievable sub 10 fs time resolution. The temporal decoding scheme utilized here for the time-to-space mapping in combination with the available probe laser limits the repetition rate at FLASH to 10 Hz [TAV11].

The second approach investigated is spectral decoding (see Figure 5). This approach has the advantage that the time-to-space mapping is a linear process and performed by mapping the spectrum of a linearly chirped laser pulse onto a normal CCD camera. The required pulse energies from the probe laser are in this case in the few 10 nJ regime and hence the requirements for the laser system are low and MHz repetition rates are easily available from commercial systems. The readout of the line spectrum can be taken with more standard CMOS line-array detector. Commercial detectors of this type are meanwhile available up to 200 kHz repetition rate [BAS17], and a purpose built line array detector is under development [ROT16].

These arguments lead to the decision to utilize spectral decoding in the demonstrator THz timing tool.

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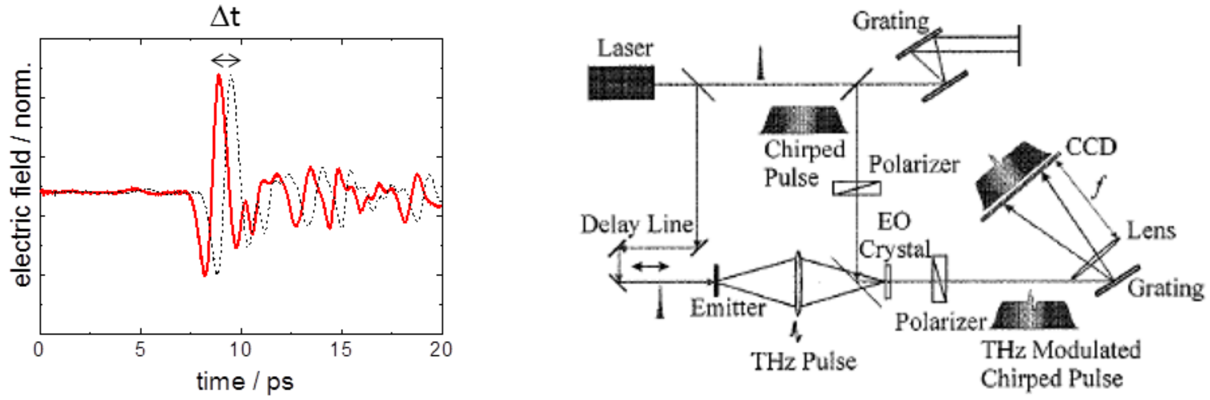

Z. Jiang, X.C. Zhang, IEEE Journ. Quant. Electr,. **36** (2000), 1214.

Figure 5: Scheme of the spectral decoding technique and example DR pulse.

2.3. Prototype set-up

The first prototype set up was assembled during 2015 – 2016 and the scheme and how it is implemented at TELBE for the benchmark experiments is shown in Figure 6. TELBE emits single-cycle pulses by means of a coherent diffraction radiator (CDR) and multicycle THz pulses by means of an undulator, both covering the frequency range between 0.1 and 3 THz at repetition rates as high as 13 MHz. The THz pulses propagate into a dedicated laboratory equipped with various experimental set-ups [GRE16]. The fs Ti:Sapphire-based amplified laser system is locked to the same master clock as the accelerator [KUN13], thereby yielding an intrinsic arrival time jitter and drift of a few ps between the laser pulses and the electron bunches generating the THz pulses [KOV17, GRE17]. The intensity stability of the TELBE THz sources depends on the accelerator settings. Fluctuations range from <10% (stable operation) to 50% (unstable operation), very similar to the case of SASE X-ray FELs. For that reason pulse-resolved monitoring of the intensity of the undulator THz pulses is performed. Note that in this test scheme the THz pulses from the undulator serve as the equivalent of the X-ray pulses from the XFEL as they originate from a second independent radiator a few metres after the diffraction radiation emitter providing the timing signal.

The prototype THz timing tool works as follows. The pulse in one branch of the laser beam is stretched by a grating-based stretcher to a duration of roughly 10 ps and overlapped with the single-cycle THz pulses from the diffraction radiator in a ZnTe crystal where its field is encoded in the spectrum. The spectrum of every second stretched laser pulse is detected by the CMOS line array, and the arrival time is deduced from the position of the main peak (see Figure 5). (The pulse duration in the other laser branch laser is kept ultra-short. This pulse is combined with the multi-cycle THz pump pulses from the undulator to probe THz-induced transient dynamics in the sample of choice. In order to perform a pulse-to-pulse background subtraction, we operate the probe laser at 200 kHz, twice the repetition rate of the two accelerator-based THz sources. The intensity of each of the THz pump pulses is determined by a fast pyroelectric detector that can resolve individual THz pulses up to a repetition rate of 200 kHz [WES11]. The primary limitation of spectral decoding in terms of the repetition rate is the read-out rate of the line-array detector measuring the laser-pulse spectrum. We utilize what is to our knowledge the fastest commercially available line-array device, operating up to a rate of 200 kHz [BAS17].

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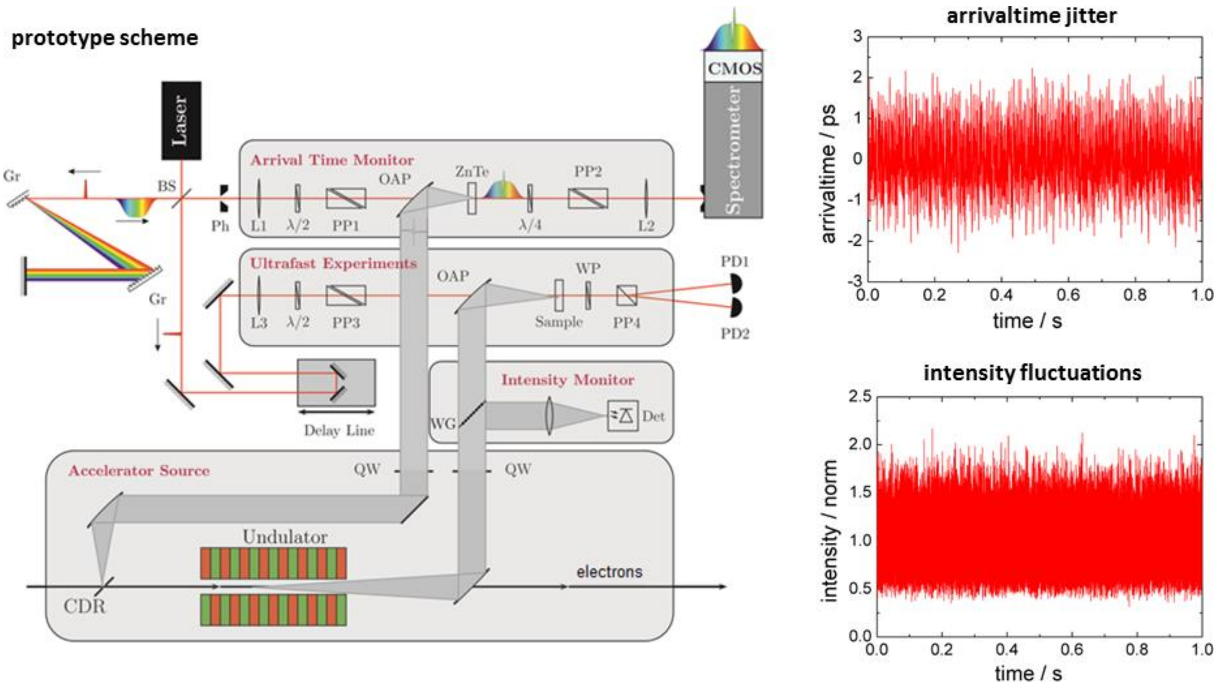

Figure 6: Scheme of the first prototype developed at TELBE (left) and example measurements for the arrival time jitter and the intensity fluctuations determined at a nominal repetition rate of 100 kHz.

2.4. THz radiator

The most optimal THz waveform for the purpose of timing is a quasi-single cycle. In electron accelerators this type of waveform is in principle emitted from bending magnet (synchrotron radiation - SR) or from so called transition or diffraction radiators (TR and DR). As can be seen in Figure 7, synchrotron radiation provides the highest spectral intensity, however in the ELBE accelerator no appropriate out coupling port was available and it was decided to set up the prototype and later the demonstrator at ELBE using single cycle THz pulses from a purpose built diffraction radiator. Ultimately this means that by choosing a synchrotron radiator such as the XFEL electron dump bending magnet one can increase the THz field and hence the SNR ratio further.

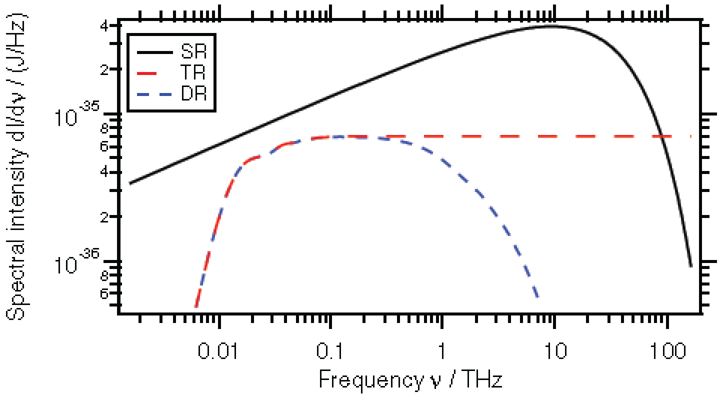

Figure 7: Exemplarily comparison of the spontaneous emission characteristics of synchrotron radiation (SR), diffraction radiation (DR) and transition radiation (TR) for the 40 MeV linear accelerator FLUTE [NAS15].

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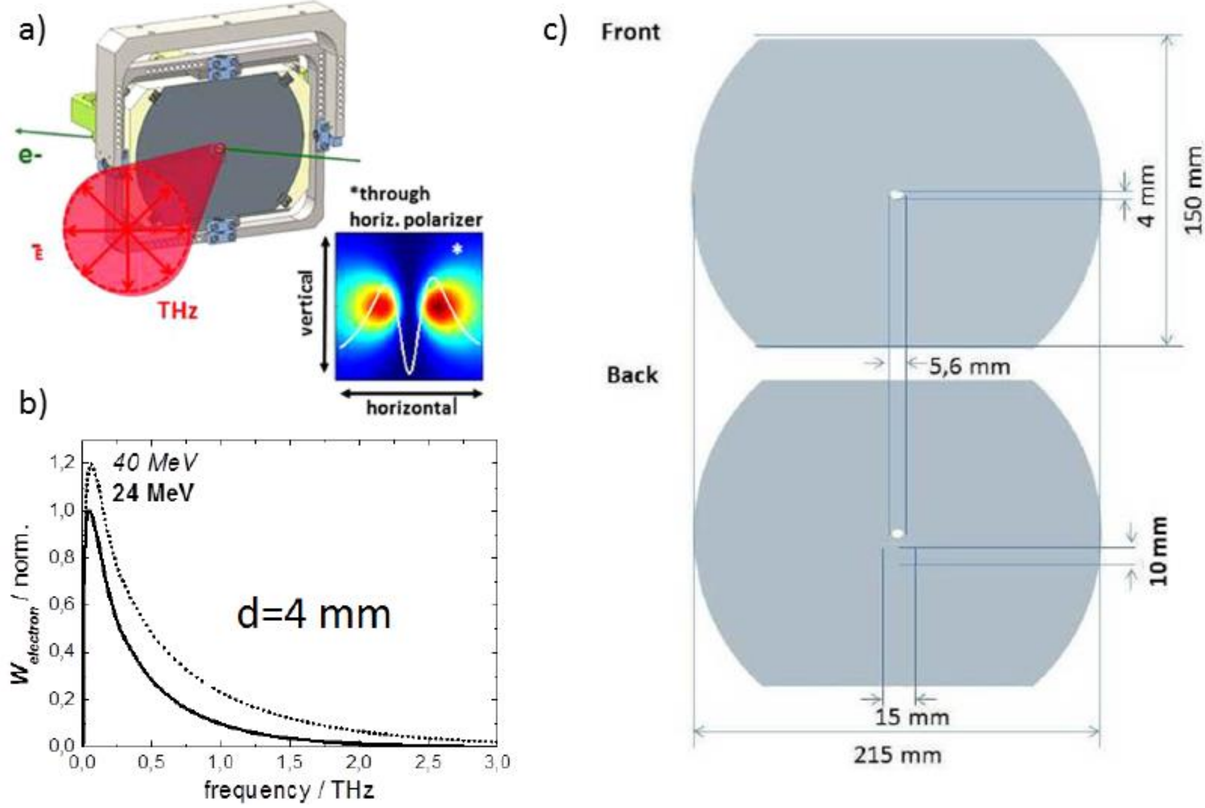

Figure 8: Diffraction Radiator as used for the prototype arrival time monitor. (a) 3D model and beam profile after going through 2 polarizing Brewster angle windows in the THz optical beamline. (b) Dependence of the expected emitted THz spectrum on the beam energy and (c) dimensions of the screen. A 200 nm film of aluminum has been deposited on a 700 µm thick silicon substrate. A central aperture of 4 mm ensures that the electron beam at ELBE can go through without any losses [GRE16, GRE17].

3. Work performed / Results / Description

In the following the results from the first tests performed with the prototype device are shown. The tests should serve to establish the reliability of the approach as well as the limits in bunch charge, repetition rate and time resolution.

3.1. Bunch Charge Limit

European XFEL is planning to operate with bunch charges between 1000 pC and 10 pC. It is important to verify if the THz timing tool would allow operation throughout this range of values. For this purpose the bunch charge dependence of the signal-to-noise value (signal is here the highest THz field, noise is the signal in absence of the THz field) was established. The results are shown in Figure 9. The charges were varied between 70 and 10 pC, while the bunch compression scheme was not adjusted. The expected linear dependence of the sampled electric field on the charge is clearly observed. The SNR below 10 pC is still between 20 and 10 which is more than sufficient to perform the arrival time measurement. The fact that the sensitivity of the monitor is clearly sufficient to measure down to charges of few pC for a beam energy of 24 MeV makes this a conservative top down estimate for the detection limit at an XFEL. In fact, higher beam energies like the GeV range at XFELs give rise to even

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higher THz pulse energies/THz fields so that even a detection limit in the sub pC regime seems reasonable.

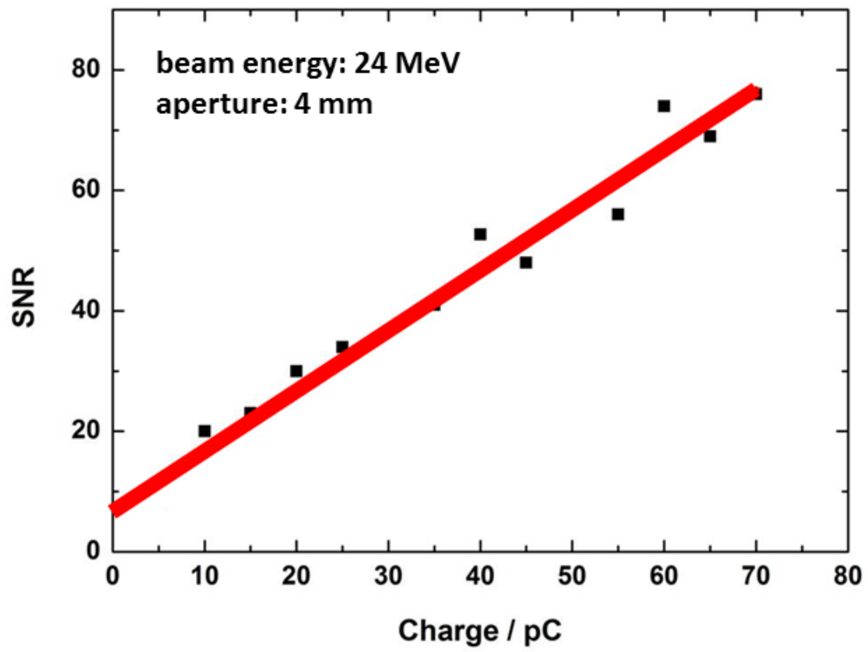

Figure 9: SNR of the arrival time measure-ment for different bunch charges. A SNR of 10 is sufficient to derive the arrival time information.

3.2. Repetition Rate Limit

As mentioned earlier in 2.2, the choice of the spectral decoding concept for the time-to-space mapping allows operation with merely few 10 nJ of pulse energy from the probe laser system. Accordingly few 10 MHz repetition rates are easily available from commercial fs laser systems. The limitation of the repetition rate therefore comes from the read-out-rate of the line-array detector utilized to image time information encoded in the line spectrum (see Figure 6). In the developed prototype device we are using, what is to our knowledge the fastest commercially available line-array device, operating up to a rate of 200 kHz [BAS17]. An increase to the nominal repetition rate of the European XFEL of 4.5 MHz depends solely on the progress of the development of a purpose built line-array detector (KALYPSO) at PSI, KIT and DESY [ROT16]. If the latter development is delayed so will be the final milestone of the THz timing tool which is to demonstrate operation at 4.5 MHz.

3.3. Time Resolution Limit

The next important benchmark is the achievable time resolution, which will be discussed below. First we show the results of benchmarking performed with the current prototype and then we discuss the fundamental limits of such a timing tool at ELBE and at XFELs.

The available fs lasers in the TELBE laboratory have a pulse duration of 100 fs. In order to derive the achievable time resolution in the sub 100 fs regime we therefore choose to indirect methods giving the results showing in Figure 10.

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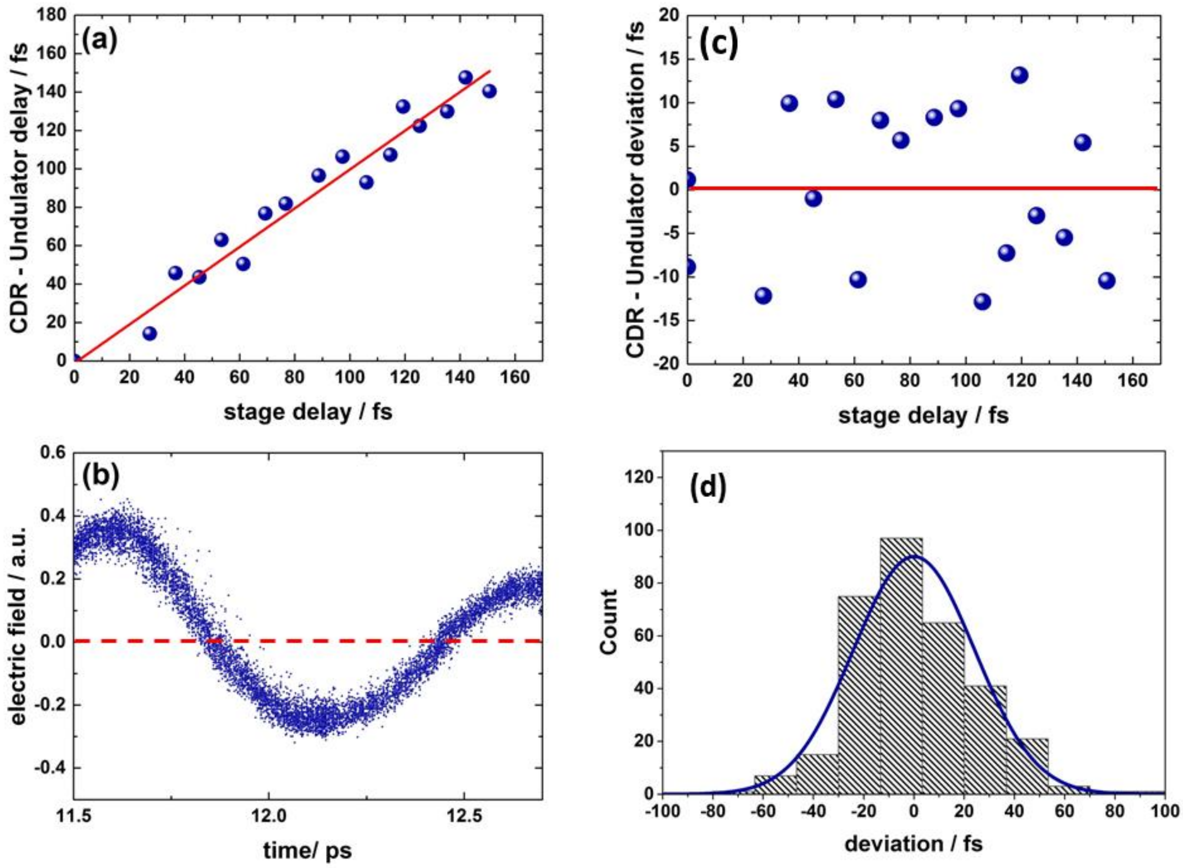

Figure 10: Benchmarking of the time resolution. (a) Measured CDR to undulator radiation delay versus delay position of the ultra-short-pulse beam. The expectation value is given as a red solid line (b) A zoom into the jitter-corrected electro-optic sampling data of the undulator radiation. (c) Deviation between the expected value from the delay position and the observed time shift between undulator and CDR. The expectation value is given as a red solid line (d) Slice through the distribution of the arrival times at the zero-field crossings at 11.8 ps and 12.5 ps (see panel (b)).

First, we measured the time delay between the CDR pulses and the pulses from the undulator. This approach makes use of the fact that photon pulses emitted from the same electron bunch can be expected to show an intrinsic synchronization [FRU09]. The CDR pulse arrival time was then delayed by an optomechanical stage in steps of a few fs, and sequential time-domain measurements of undulator pulses were performed at each step. The observed shift of the multicycle pulses with respect to each other is plotted against the delay stage position in Figure 10a. The extracted time-shift values vary by 28 fs (FWHM) or 13 fs (rms) from the expectation value (see Figure 10c). A second way to estimate the time resolution is to directly measure the linewidth of the jitter-compensated data at zero-field crossings as shown in Figure 10b. The slice of the distribution with zero intensity shown in Figure 10d gives another estimate for the achieved time resolution which here equals 24 fs (rms) or 56 fs (FWHM), slightly larger than the postulated optimal achievable time resolution which is due the contribution of detector noise to the observed electric field values.

In the following we now discuss the fundamental limits of the scheme.
The arrival time of the THz pulses with respect to the probe laser is determined through the phase of the electric field of the far-field THz pulses. In spectral decoding [JIA98], the time

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axis is mapped onto the instantaneous frequency of the laser pulse. In our setup, the electro-optic signal is detected by a CMOS line array [BAS17] located in the focal plane of a Czerny-Turner grating spectrometer. The limit for the achievable temporal resolution is predominantly determined by: (i) the CMOS pixel-to-time conversion (including the chirp and the spectrometer dispersion) and (ii) the detection noise.

In the experiments, Ti:Sapphire laser pulses with a wavelength of 800 nm and a spectral bandwidth of 10 nm are linearly chirped and stretched to a duration of roughly 10 ps. After the interaction in the electro-optic crystal has encoded the THz field into these pulses, they are dispersed by a grating and imaged onto the line array. The current set-up makes use of 2048 of the 4096 10-µm pixels in the array. If the full line focus corresponding to 10 ps were to exactly match this part of the array, the conversion would be 5 fs (FWHM) per pixel. During experimental runs, we operated normally with a line focus that is a factor of 2 smaller than the active area, leading to the time resolution $\Delta t_{monitor}$ = 12 fs (FWHM) or 5 fs (rms), which is shown in Figure 10 along with the single-shot spectra of four consecutive THz pulses.

However, it is important to discuss the experimentally observed time resolution Δt_{exp} = 28 fs (FWHM) or 13 fs (rms) can be further improved since it is presently by a factor of ~3 larger than the calculated time-resolution of the monitor $\Delta t_{monitor.}$ The experimentally observed time resolution is not only affected by $\Delta t_{monitor}$, but also by the limit for the intrinsic synchronization of the two independent THz sources $\Delta t_{intrinsic}$ and the instability between the two transport paths $\Delta t_{transport}$ which in our current set-up have individual lengths of several metres. Given that these error sources are independent, one has

$$\Delta t_{exp} = (\Delta t_{monitor}{}^2 + \Delta t_{intrinsic}{}^2 + \Delta t_{transport}{}^2)^{1/2}$$

Assuming the previously observed value for $\Delta t_{intrinsic}$ of ~12 fs (FWHM) [FRU09] and the calculated value for $\Delta t_{monitor}$ = 12 fs (FWHM) as correct, results in an estimate for the unknown contribution $\Delta t_{transport}$ of 25 fs (FWHM). This value is reasonable when considering that the timing set-up and the experiment are for logistical reasons performed on two different laser tables leading to independent optical paths of several metres.

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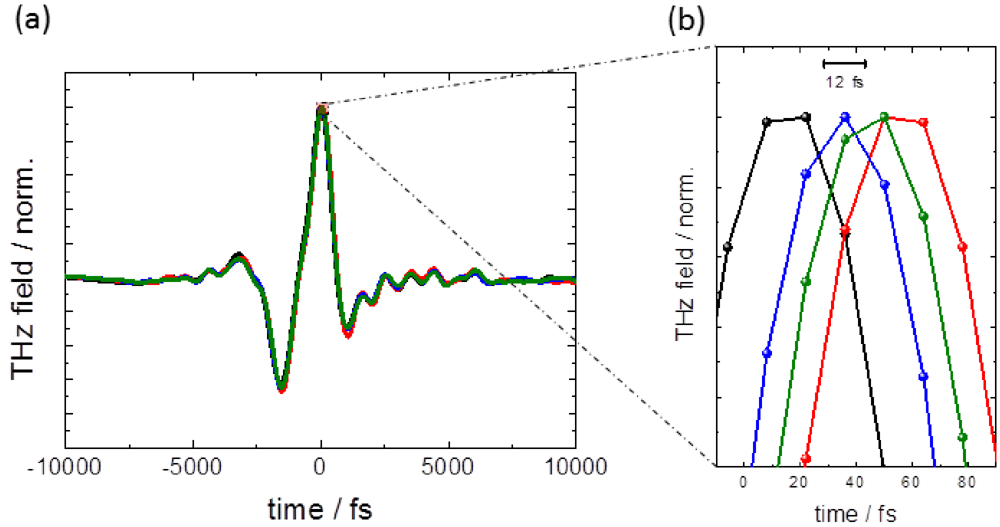

Figure 11: (a) Four consecutive single-shot measurements of THz pulses from the coherent diffraction radiator. (b) Magnified section around the signal maxima. They indicate the arrival time uncertainty. The repetition rate in these measurements was 100 kHz.

The time resolution of the monitor $\Delta t_{monitor}$ can be further optimized in several ways. The most obvious approach while maintaining the current optical set-up would be to stabilize the accelerator drifts and jitter below 1 ps. In this case the laser pulse can be stretched less, from 10 to 1 ps, while its bandwidth remains dispersed across the CMOS line array. Then the time difference from the stretcher across one pixel drops by a factor of ten and $\Delta t_{monitor}$ decreases into the 1-fs regime. Such stability has been frequently demonstrated at other 4th-generation light sources based on SRF accelerator technology [RED11] where active feedbacks can provide even sub-100-fs arrival time stability [SCH15]. If this is matched at the imaged time window, even the sub-fs regime may be accessible.

However, it is likely $\Delta t_{intrinsic}$ and $\Delta t_{transport}$ that will dominate the time resolution in the application in XFELs. Assuming the THz pulse utilized for the timing would be generated by ultra-short electron bunches in the XFEL accelerator via synchrotron radiation will result in a distance of more than 500 m between the THz source acting as time prompt and the actual experimental endstations in the European XFEL experimental hall. As shown previously in the prototype experiments at the FLASH FEL [FRU09, TAV11] a distance of more than 60 metres, between the THz emitter and the actual experiment to be timed, can still yield a sub 10 fs (FWHM) time resolution. On the contrary TELBE with only 23 m of optical transport from the THz source to the THz timing tool exhibits a time resolution of 30 fs (FWHM).

3.4. Reliability and Operational Experiences

To make timing tools applicable real-world user experiment at large scale facilities requires a sufficient robustness to provide the timing information with a duty cycle of at best 100%. In the following we present results from the application of the prototype THz timing tool during friendly user operation at the TELBE THz facility. TELBE is in friendly user operation since 07/2016 and the monitor has been used in roughly 80% of all shifts. Because the timing jitter of ELBE is in the few ps range [KOV17] postmortem arrival time correction is required in essentially every ultra-fast technique. Below the results for two exemplarily performed

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benchmark experiments are shown: (i) THz Time-domain spectroscopy on the emitted undulator radiation (Figure 12) and TR Faraday probing of a THz driven spin wave in the prototype antiferromagnet NiO (Figure 13).

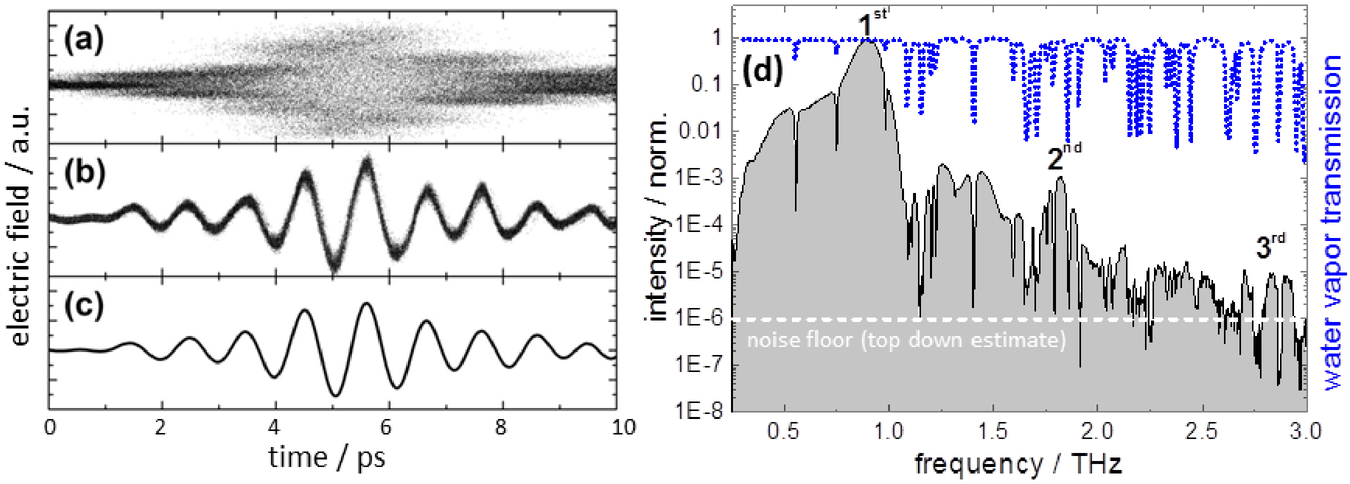

Figure 12: Data-sorting process for the benchmark THz-spectroscopy experiment. The undulator is tuned to a central frequency of 0.9 THz; its electric field is measured by sequential electro-optic sampling in the time domain. (a) Unsorted raw data in which each dot represents a measured value of the THz electric field (y axis) plotted against a time value determined by the optical delay position (x axis). The few-ps jitter prevents us from resolving the individual field cycles. (b) After correcting the time axis for jitter, the blurring is reduced to below 30 fs (FWHM). The remaining blur is due to the intensity fluctuations during the experiment. (c) Normalized electric-field data obtained by averaging the electric field in bins of 50 fs. (d) Resulting THz frequency-domain spectrum when evaluating the full time-domain measurement over 120 ps, plotted on a logarithmic scale (grey shaded). Higher harmonics up to the 3rd order are observed with a dynamic range of over five orders of magnitude. The measurement was performed in atmosphere and the narrow water absorption lines (blue dotted line) are clearly resolved up to 3 THz. The narrow dashed white line indicates the top down estimate of the smallest detected signal which is of the order of 10^{-6}. Since the noise floor clearly is lower than this, the maximum dynamic range is 10^{6} or higher.

The benchmark experiments and the overall experiences of the first eight months of friendly user operation lead to two main conclusions. Firstly, the actual timing measurement is really robust. There has actually been no failure during any of the beamtimes starting from 07/2016. Secondly, at high repetition rate, the main bottle-neck lies within the data handling and near real-time data analysis. Presently, TELBE is operated with a repetition rate of 100 kHz quasi-cw. The images from the line array detector which contain the arrival time information have a size of 3 kB and are currently permanently stored because they are considered as part of the original data set. This generates a memory requirement of 300 MB per second resulting in a memory requirement of 13 TB per 12 hour shift. Writing to memory and/or online arrival time sorting currently leads to latency times, lowering the achievable duty cycle to less than 100%. Within the next two years, upgrades of the data-network capacity and of the storage speed will allow to achieve 100% duty cycle. FPGA architecture will allow realtime-analysis in parallel.

One important aspect is that the timing signal is a single peak as can be seen in Figure 11. This makes the scheme comparatively tolerant against sensitivity variations of e.g. the line array detector.

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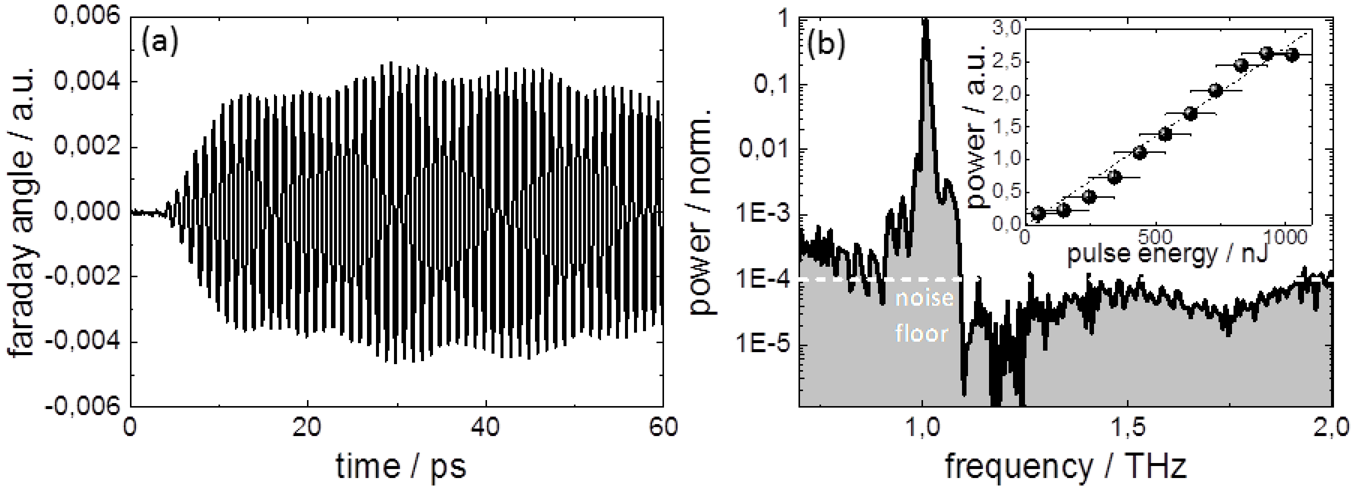

Figure 13: Benchmark THz-pump laser-probe experiment on THz-field-driven coherent spin precession in antiferromagnetic NiO. (a) Transient Faraday measurement of the spin deflection induced by a 1 THz pulse tuned in resonance with the antiferromagnetic resonance. (b) Resulting frequency-domain power spectrum on a logarithmic scale. The white dashed line denotes the noise floor of in the measurement which according to reference [15] allows deducing a maximum dynamic range of 10^4. The THz pulse energy was varied between by 0 and 1100 nJ during the measurement. By utilizing the pulse-resolved detection of the intensity and the high number (~10^6) of pulses involved, one can not only measure the spectrum of the coherent spin wave excitation, but simultaneously determine the fluence dependence of the pump-probe signal (see inset).

Repetition rate	Camera	ADC 14 bits 8 channels	Data rate	Storage needed for 30 shifts of 12 hours each
101 kHz	Commercial	10 MS/s	505 MB/s	654 TB
101 kHz*	Commercial	10 MS/s	143 MB/s	185 TB
4.5 MHz	KALYPSO	5 GS/s	10.3 GB/s	13.3 PB
4.5 MHz*	KALYPSO	5 GS/s	6.3 GB/s	8.2 PB

Table 1: Current and future demands of the arrival time monitor together in combination eight 14 bit ADC channels when operated in quasi-cw mode for 4 different scenarios (101 kHz and 4.5 MHz repetition with and without* storage of the original image files containing the timing information). As can be seen, one experimental endstation equipped with the THz timing tool generates few 100 TB of data in cw operation for 30 x 12 hour shifts (15 days x 24 hours). The situation relaxes at European XFEL because of the macro pulse mode and the nominal merely 27000 pulses / s to a still substantial storage requirement of 180 TB.

4. Synergy Aspects

4.1. Applicability to European XFEL/PSI/ELI

4.1.1. THz timing tool based on superradiant THz sources at XFELs

The THz timing tool as currently envisioned requires relativistic electron bunches with at minimum few pC charges and a duration shorter than a few ps. It hence in the current form

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is well suited to be readily employed at XFELs (such as the European XFEL or the Swiss FEL). Prerequisite is the availability of sufficient space for a suitable THz radiator and either an optical transport line for the far-field THz pulses to a timing tool outside of the accelerator or an adequate space in the accelerator tunnel. In both cases access to a suitable NIR fs laser system (few 10 nJ pulse energy, 1.25% bandwidth) that is synchronized with the pump probe laser system at the experimental endstations is required. As one of the next steps in this project it will be evaluated if and how the fs laser used for the fibre link stabilization at European XFEL is suited for operating the THz timing tool. It also needs to be verified whether diffraction radiator emission [KOV17] or dipole and/or edge radiation from bending magnets [STO13] or edge radiation from the XUV undulators [TAV11] is used. The footprint of the actual timing tool is small and can be less than 1 m x 1 m.

4.1.2. ELI facilities and alternative applications at XFELs

On the contrary, the straight forward application at the ELI facilities is less obvious. Firstly, timing jitter is not the most crucial problem in experiments that utilize different particle beams generated by the same driving laser. Secondly, most applications at ELI do not generate electron bunches with relativistic energies, superradiant THz pulses are therefore not available.

However, during the course of the project we became aware of a possible alternative way to generate single-cycle THz pulses that may make our timing tool of relevance for the ELI facilities and moreover may enable an additional application as experiment-near timing tool at XFELs. In general it is a well-established technique to generate single cycle THz pulses from NIR fs lasers by either optical rectification or by means of photoconductive (antenna) emitters. Currently discussions have started to investigate if suitable THz pulses can be generated via X-ray excitation of matter. If so then the actual location of the THz timing tool could also be directly at the experiment and one may be able to make full use of its capabilities with respect to robustness, temporal resolution and high-duty cycle.

5. Conclusions

The development of the THz timing tool demonstrator for the European XFEL is ahead of time. Benchmarking experiments and test measurements with a first prototype proof [KOV17] that it can operate in the full bunch charge regime foreseen for the European XFEL. The time resolution of the monitor itself can be in the sub 1 fs regime but the achievable time resolution at European XFEL would likely be governed by the actual location and transport of the optical beams and signals to and from the THz timing tool. The prototype device allows operation up to a repetition rate of 200 kHz and is based on a commercial line array detector [BAS17]. Whether operation up to 4.5 MHz can be realized, solely depends on the development of the purpose-built the KALYPSO line array detector [ROT16] (see Table 1). If this development is delayed then the final milestone for the THz timing tool to build and test a demonstrator device at the ELBE accelerator operating at 4.5 MHz will also be delayed. It should be noted that the THz timing tool is due to the single peak nature of the actual timing signal comparatively tolerant against sensitivity issues.

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7. Publications

S. Kovalev *et al.*, *Probing ultra-fast processes with high dynamic range at 4th-generation light sources: Arrival time and intensity binning at unprecedented repetition rates*, Structural Dynamics 4, 024301 (2017); doi: http://dx.doi.org/10.1063/1.4978042

B. Green, *Superradiant Terahertz Sources and their Applications in Accelerator Diagnostics and Ultra-fast Science*, PhD thesis, KIT 2017

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