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THz-based arrival time monitor

Lead Beneficiary: HZDR

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Deliverable Type	
R = Report DEM = Demonstrator, pilot, prototype, plan designs DEC = Websites, patents filing, press & media actions, videos, etc. OTHER = Software, technical diagram, etc.	DEM
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Abstract

In EUCALL Deliverable 7.3 “THz-based arrival-time monitor at FEL and ELI facilities” [1] we discussed the concept and presented first benchmarking results for an arrival-time monitor based on the single-shot electro-optic detection of THz pulses generated by relativistic electrons. Different techniques for single-shot electro-optic detection and data handling were evaluated with respect to limits in bunch charge, limits with respect to the maximal possible repetition rate and limits in time resolution. The achievable reliability and the dynamic range of the different concepts was considered in addition since the device needs to eventually operate in 24/7 user operation.

As a result the choice was made to utilize the spectral decoding technique [3]. A diffraction radiator [4] was designed and used as emitter of superradiant single-cycle THz pulses which acted as the time prompt [1]. The performance was subsequently benchmarked by successfully performing a THz pump laser probe benchmark experiment (see Figure 1) [2]. Since Deliverable 7.3, the arrival-time monitor has been further developed and transformed into an operational demonstrator. The following progress has been made: (i) the demonstrator was operated reliably and successfully in several user experiments (see [5, 6, 7]) and (ii) the data analysis speed was significantly increased by implementing multi-thread concepts with the goal to get as close as possible to near-real-time processing. Additionally, an alternative concept was developed as a spin-off of the spectral decoding technique that may allow intrinsic synchronization between lasers and accelerator-based sources by THz slicing for some specific experiments [8].

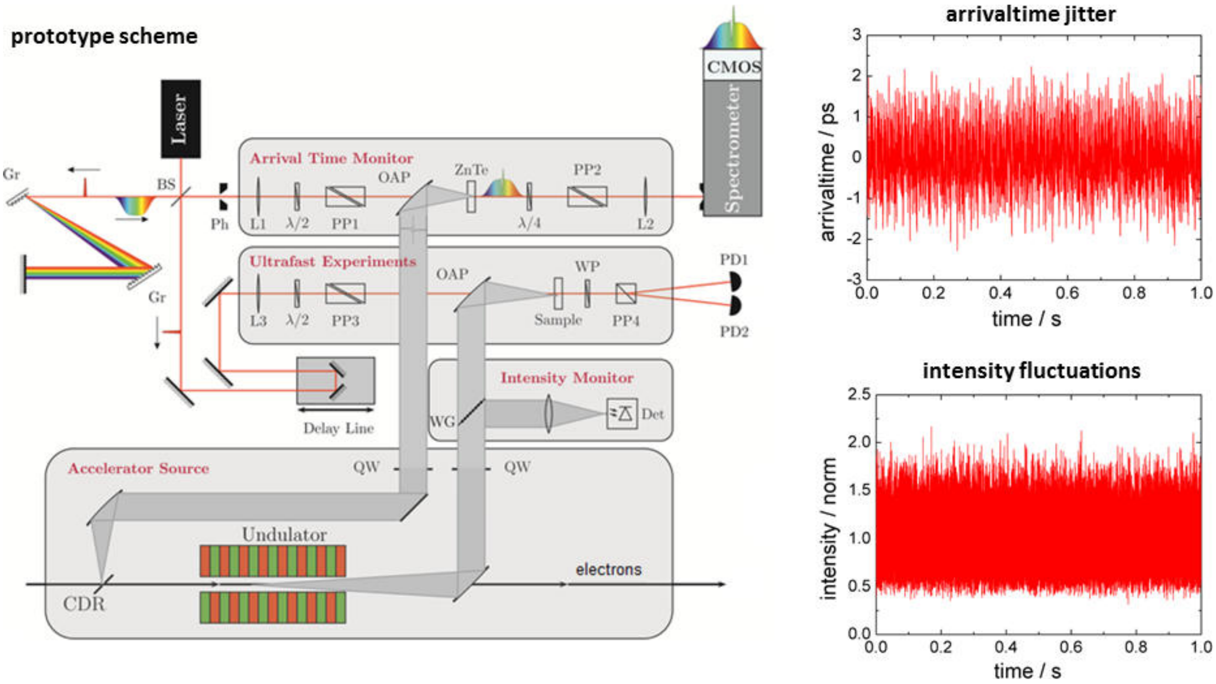

Figure 1: **(left) Scheme of the prototype developed and installed at TELBE (top right) arrival-time jitter over one second (bottom right) intensity fluctuations over one second (taken from [1,2]).**

1. THz-based arrival-time monitor prototype

The prototype is currently installed and has been tested at the TELBE THz facility [4] and consists of the following parts: the diffraction radiator (see Figure 2a), the NIR probe laser (see Figure 2b), the stretcher for the probe laser pulse that generated a ~10 ps long pulse (see Figure 2c), the electro-optic sampling setup to encode the arrival-time information into the spectrum of the NIR laser pulse (Figure 2d) and the spectrometer with the CMOS line-array detector that decodes the arrival-time information from the spectral back to the time-domain (Figure 3a). The length of the optical path of the diffraction radiator from the source to the electro-optic crystal is ~25 meters and utilizes 16 metal mirrors (planar, toroidal and parabolic).

The arrival-time monitor can be used to time ultrafast THz pump laser probe experiments with pulses from a second THz radiator – a superradiant THz undulator (see Figure 4) for the purpose of benchmarking the performance [2]. The length of the optical path for the pulses from the THz undulator to the pump probe experiment is also ~25 meters and utilizes 14 metal mirrors.

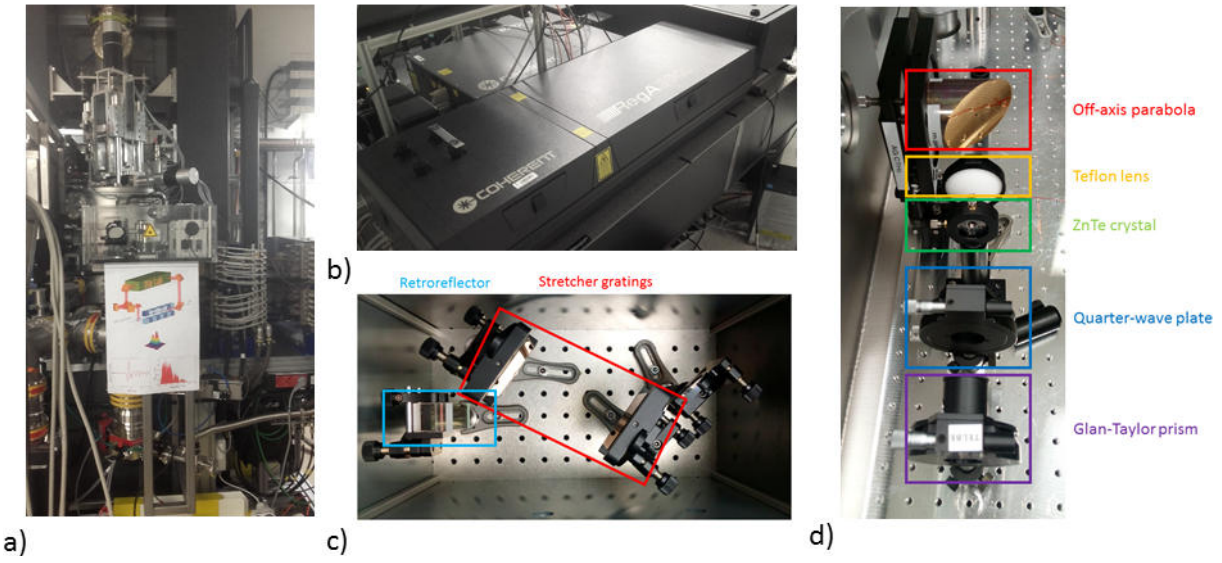

Figure 2: (a) Coherent diffraction radiator in the ELBE accelerator emitting the single-cycle THz pulse used as the time prompt, (b) NIR femtosecond probe laser system that provides linearly chirped 100 fs pulses at 800 nm wavelength (type: COHERENT Reg A 9000), (c) pulse stretcher used to generate the ~ 10 ps long NIR pulse employed to encode the THz pulse waveform into its linearly chirped spectrum, (d) electro-optic set-up with a ZnTe crystal in which the actual encoding of arrival-time into the pulse spectrum takes place.

2. Performance

The prototype allows operation at low bunch charges down to the few pC regime at the few 10 MeV accelerator driven TELBE facility and it can be predicted from scaling considerations of the emitted THz pulse energies that at the GeV accelerator driven European XFEL, operation in the sub pC regime is very well possible [1]. The THz-based arrival-time monitor prototype can, besides routine mode of operation in the few 10 pC to 100 pC regime, thereby readily be employed also in more special operation modes such as single mode lasing [9].

The repetition rate of the prototype arrival-time monitor is currently still 100 kHz utilizing a commercial line array detector [10] because the KALYPSO 3.0 line-array camera, operational at 4.5 MHz, was not available in due time for this report. However, table-top tests with a KALYPSO 1.0 line array detector (see Figure 3b) and work on the subsequent data processing ensures that once available it can readily be implemented and 4.5 MHz operation (with the KALYPSO 3.0 line array detector [11]) will be possible. After the EUCALL project has finished part of the consortium plans to continue to upgrade the line array detector and the data processing to 13 MHz operation [12] in order to match the maximum repetition rate available from the ELBE accelerator [13].

The prototype achieves a timing accuracy of better than 30 fs (FWHM) [1, 2]. It should be noted that this accuracy includes the instabilities (primarily drifts) in the two optical transport lines of in integral roughly 50 meters and 30 mirrors. We estimate that at European XFEL the arrival-time monitor could achieve similar or even better accuracy. Assuming that the THz pulses are generated at the exit of the x-ray undulators and the arrival-time monitor would be located in its close vicinity, then the corresponding x-ray pulses would be transported over a considerably longer distance of 900 meters. However,

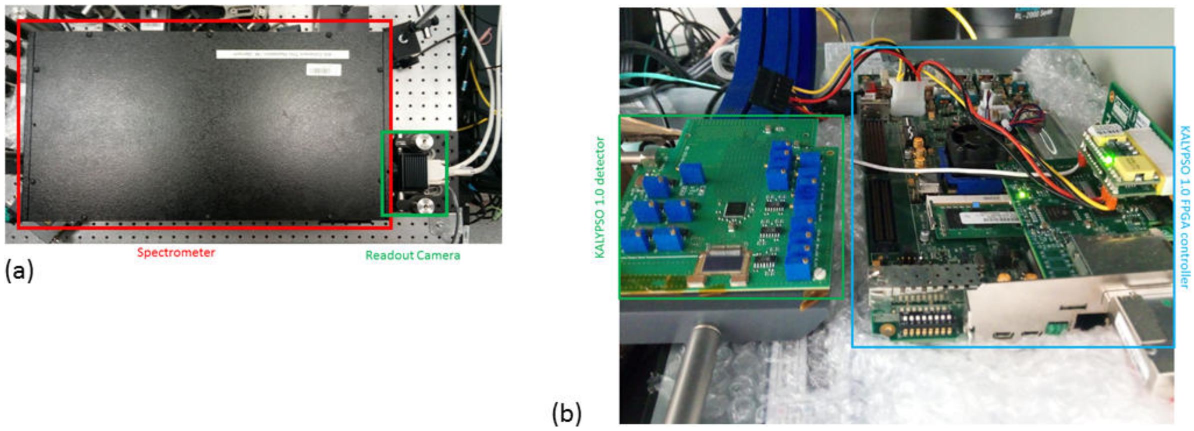

Figure 3 (a) Spectrometer *(type: Acton Standard Series SP-2556 Imaging Spectrograph)* and readout camera *(type: spL4096 140km - Basler sprint*) that enables operation at 100 kHz cw, (b) KALYPSO 1.0 line array detector and the corresponding readout FPGA controller, this device enables operation at 900 kHz and data-acquisition was successfully tested with table-top equipment at this repetition rate.

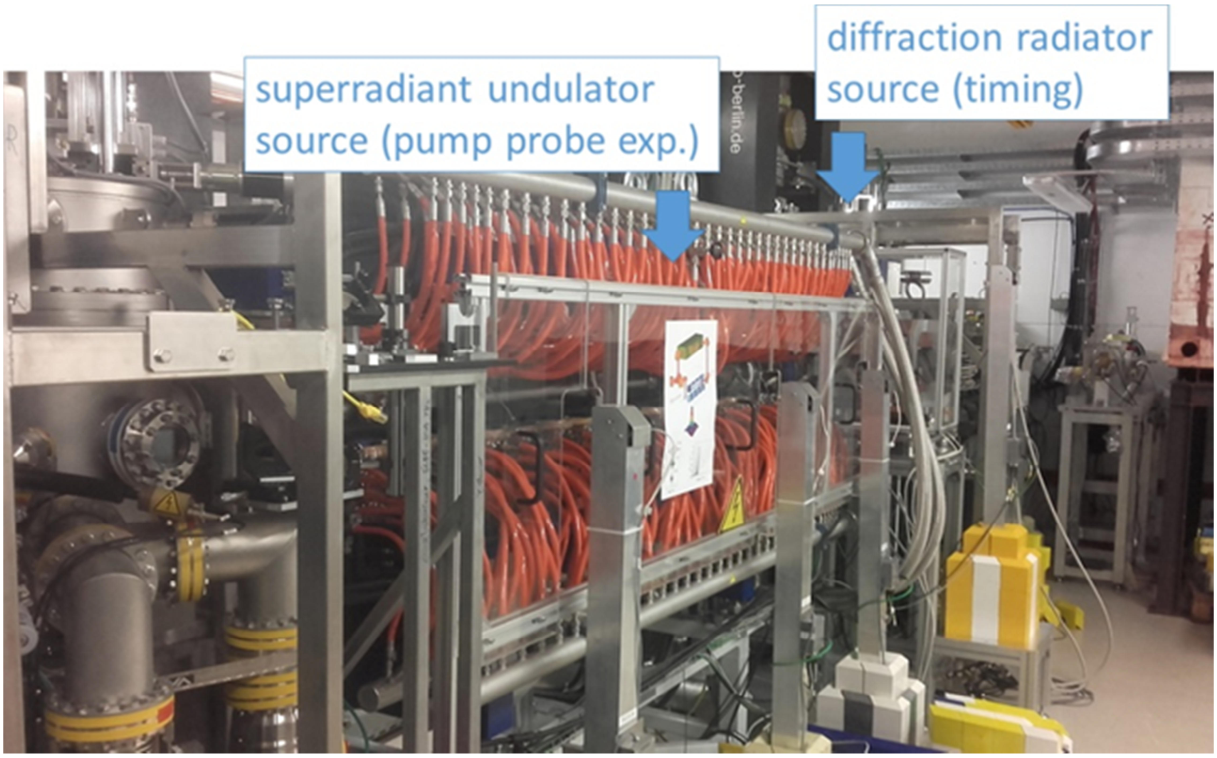

Figure 4: Arrangement of the diffraction radiator and the superradiant undulator in the ELBE accelerator. The distance between the 2 sources is ~ 4 meters. The THz light pulses are transported to the TELBE laboratory in 2 independent beamlines each of approximately 25 meter length [4] and 13 respectively 15 metal optics.

the x-rays impinge only on 3 mirrors M1-M3 about 450 m downstream from the undulator exit before reaching the FXE endstation which keeps potential instabilities rather low. Moreover, the temperature stability at the European XFEL is much better than at TELBE where the accelerator caves are sealed during operation because of radiation safety issues due to the quasi-cw operation. The primary goal within EUCALL to provide sub-ps timing resolution and allow the preselection of pulses that are outside of the timing window of the liquid-jet based arrival-time monitor will in any case be feasible.

Installation of the THz-based arrival-time monitor at the European XFEL within the duration of the EUCALL project was not possible due to prioritization of the early user experiments at the European XFEL. For this reason the intended testing of both arrival-time monitors against each other (Task 7.1.3.) could not be performed as planned at the European XFEL but an alternative test was performed at the TELBE THz source. For this purpose the liquid jet utilized in the liquid-jet based monitor was set-up at the TELBE beamline and the THz-based arrival-time monitor at the diffraction radiator beamline was utilized to time the change of the optical properties of a liquid water jet induced by THz pulses from the THz undulator source (see Figure 5). As fundamental mechanism we choose the so-called Terahertz-field-induced second-harmonic-generation (T-FISH) [14] in which the THz field induces a transient orientation of the molecular dipoles which lead in turn to second harmonic generation. The

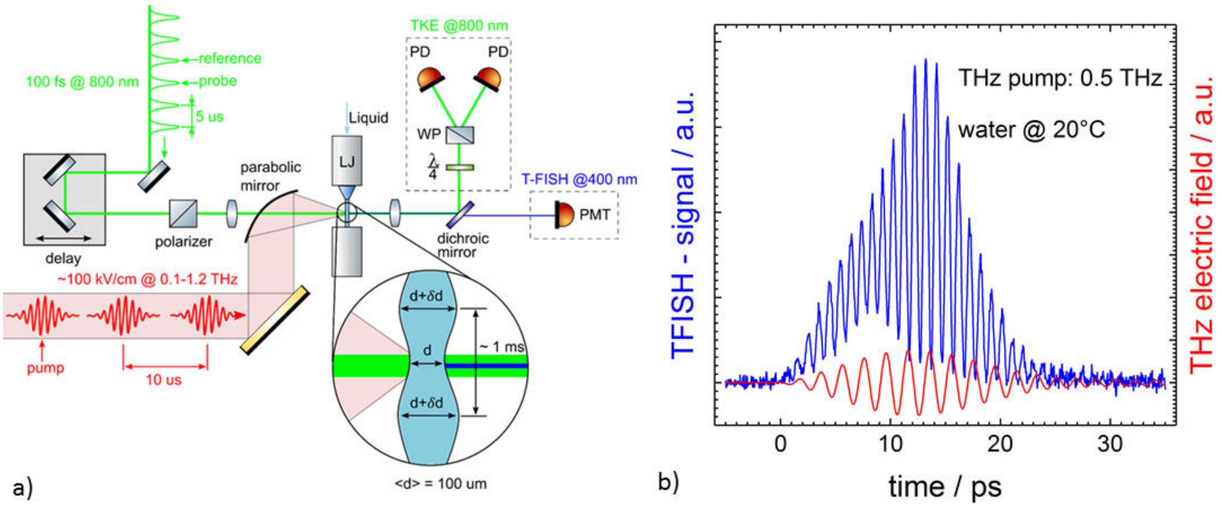

Figure 5: (a) Scheme for Terahertz-field-induced second-harmonic-generation (T-FISH) and Terahertz Kerr effect (TKE) measurements installed for the liquid jet experiments at TELBE. The implemented liquid jet is of the same type than used in the liquid-jet based arrival-time monitor. Multi-cycle THz pulses from the THz undulator source are used to modify the alignment of the water molecules in the jet leading to generation of the second harmonic of the incident fs laser pulses at 400 nm. (b) Observed T-FISH signal in water (blue) and incident 0.5 THz pulse from the superradiant THz undulator (red). The transient molecular alignment is independent of the field direction and hence shows up as periodic modulation at twice the excitation frequency at 1 THz.

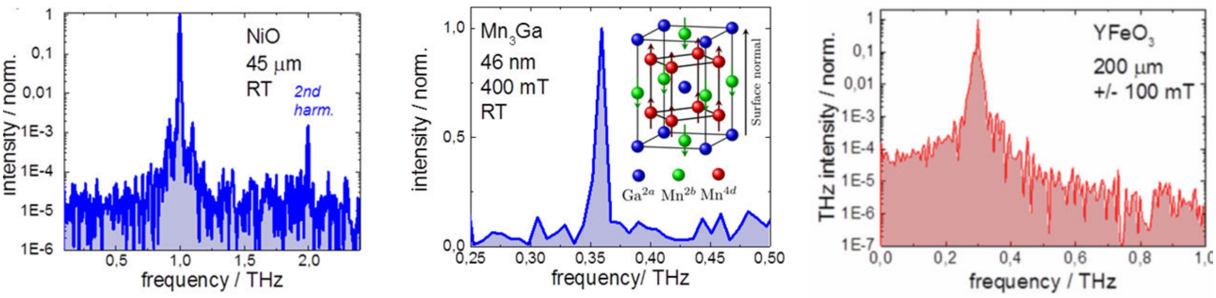

Figure 6: Example THz pump laser probe experiments at TELBE enabled by the THz-based arrival-time monitor (left) THz driven antiferromagnetic (AFM) spin wave in NiO, (middle) THz driven ferromagnetic resonance in $Mn_{3-x}Ga$, (right) THz emission from THz driven ferromagnetic resonance in YFeO3. The measurements were performed in the time-domain and the shown frequency spectra are derived from Fourier transformation.

experiment was performed with a 0.5 THz multicycle pulse from the superradiant THz undulator and was timed with the THz-based arrival-time monitor utilizing pulses from a diffraction radiator positioned several meters upstream of the undulator in the electron beamline. The alignment of the molecular dipoles in water in the THz electric field is independent of the THz field direction. The T-FISH signal is hence modulated with the frequency of the rectified THz field of in this case 1 THz.

Since the completion of Deliverable 7.3 in March 2017, the monitor was successfully employed in 19 user experiments at TELBE. Some early results are shown in Figure 6 and are published in ref. [5, 7].

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3. Synergy Aspects

Within EUCALL it has been shown that the THz-based arrival-time monitor is robust and reliable and furthermore can provide a timing accuracy in the few 10 fs regime. Besides its discussed application at the European XFEL, the concept is also of interest for other European light sources. It has been already transferred to the FLASH THz facility [16] and would also be easily applicable at the TERAFERMI beamline at FERMI. Furthermore a beamtime at the FERMI FEL has been granted in 2019 that investigates into the possibility to generate THz pulses from the spent x-rays in an appropriate solid and utilize the generated THz pulse for arrival-time measurements.

4. Conclusions

The THz-based arrival-time monitor prototype is an important ingredient to the particular goal of the PUCCA work package "to develop schemes to measure precise arrival time of pulses from a distant light source (with respect to an independent closer light source) at MHz repetition rates". The prototype is currently operated at 100 kHz, because the 4.5 MHz capable KALYPSO line array detector has not yet been available. However there is no doubt that operation at 4.5 MHz will be feasible.

The prototype is in operation at the TELBE user facility and has enabled several successful pilot experiments [4,5,6,7,15]. The robustness and reliability of the monitor under user experiment conditions has thereby been proven.

Once approved, a THz-based arrival-time monitor of this type could be installed in the SASE1 photon tunnel of European XFEL.

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6. Publications

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