# X-RAY PHOTON TEMPORAL DIAGNOSTICS FOR THE EUROPEAN XFEL

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*Abstract*

The European XFEL facility (XFEL.EU), which will be commissioned starting 2016 shows exceptional features with its high delivery rate of light pulses and extremely high average brilliance. Characterizing the temporal properties of the FEL pulses on a shot-to-shot basis is important and challenging. Here we report about the concept and recent progress concerning temporal diagnostics for XFEL.EU. Spectral encoding and THz-streaking are the techniques which will be implemented to deliver arrival time and pulse duration monitoring while coping with the high repetition rate and high brilliance of XFEL.EU.

## INTRODUCTION

European XFEL (XFEL.EU) will be commissioned in 2016 and become operational in 2017. Its most prominent advantages will be its extremely high number of light pulses per second (27000 p/s) and two or three orders higher average brilliance than other FEL facilities. The FEL pulses in XFEL.EU are produced in 10 Hz bunch trains that contain up to 2700 individual pulses within the 600 μs time of one bunch train, corresponding to a pulse separation of 220 ns between individual light pulses or a 4.5 MHz repetition rate, as illustrated in the conceptual (CDR) and technical design reports (TDR) [1-5].

When choosing and designing the timing tools for XFEL.EU, the extremely high peak brilliance and high repetition rate must be addressed. A universal independent shot-to-shot temporal tool shall be developed, which is expected to be applicable in a broad range of x-ray photon energies and with various x-ray pulse lengths under different operation modes.

Adapted from attosecond (as) metrology, where the as XUV pulses generated via high harmonic generation (HHG) are characterized by using a few-cycle near Infrared laser pulse [6-8], the x-ray THz streaking technique was experimentally successfully employed for single shot soft x-ray temporal diagnostic [9-12], utilizing THz radiation from a THz undulator or an external laser based THz source. Very recently, hard x-ray streaking was successfully demonstrated as an arrival time monitor and pulse length monitor in SACLA across a broad photon energy range of 5 to 12 keV.

Independent photon arrival time monitoring based on spectral encoding was first demonstrated by LCLS and is also planned for XFEL.EU. It needs to be shot-to-shot burst mode compatible, and ideally permit extraction of a veto signal. Since spectral encoding was demonstrated so far only for repetition rates of 10 Hz to 120 Hz, an extension to MHz repetition rates for XFEL.EU has yet to be studied and developed.

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## STREAKING ELECTRONS WITH THZ RADIATION

The energy distribution of photoelectrons ejected from noble gases ionized by x-ray pulses can be broadened and shifted by an external optical field depending on its ionization time instant, and the temporal properties of the x-ray pulse are then mapped onto the kinetic energies of the photoelectrons. One can thus uniquely determine the relative time delay between x-ray and external field as well as the pulse length of the x-ray pulse by comparing the photoelectron energy with and without external streaking field.

Long wavelength THz pulses are chosen to get rid of the intrinsic time jitter of the x-rays since longer wavelength streaking fields give rise to a larger linear streaking region which is less sensitive to the x-ray time jitter.

A single-cycle THz pulse, generated by tilted pulse front pulses in a Lithium Niobate (LN) crystal, with zero crossing temporal duration of ~600 fs to 1 ps, will be implemented [13]. An example of a THz pulse, generated from 2.5 mJ, 1 kHz, 800 nm is illustrated in Fig. 1. The THz radiation has a central frequency of 0.65 THz and extends up to 3 THz, with the electric field strength of 130 kV/cm. More effect will be studied and further optimizations to the THz pulse shape and field strength will be done, e.g. by cooling down the LN crystal or using organic crystals like DAST for higher frequency and higher field strength THz generation [14].

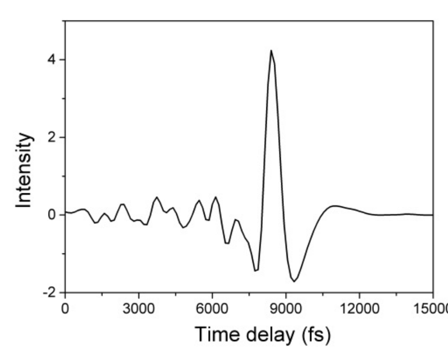


Figure 1: Typical single-cycle THz pulse from LN using the tilted pulse front method.

It should be pointed out that the temporal resolution of THz streaking is related to the THz field strength and the initial photoelectron energies and is limited to the bandwidth of the x-ray pulse, the energy resolution of the electron time of flight (eTOF) spectrometer and shot-to-





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shot time jitter. The temporal resolution can be improved by either applying a more intense THz field or streaking higher energetic electrons for a given eTOF spectrometer.

We performed a theoretical analysis of THz streaking for different photon energies, pulse durations and temporal jitter using the THz field shown in Fig. 1 with a peak electric field of 200 kV/cm. Examples of the Kr 2p streaking traces below photon energy of 2 keV with different pulse length and time jitter can be found in the left column of Fig. 2. Each energy spectrum is an average of 50 shots, and 300 corresponding shot-to-shot photoelectron energy spectra can be found in the right column of Fig. 2 for the fixed time delay of zero delay.

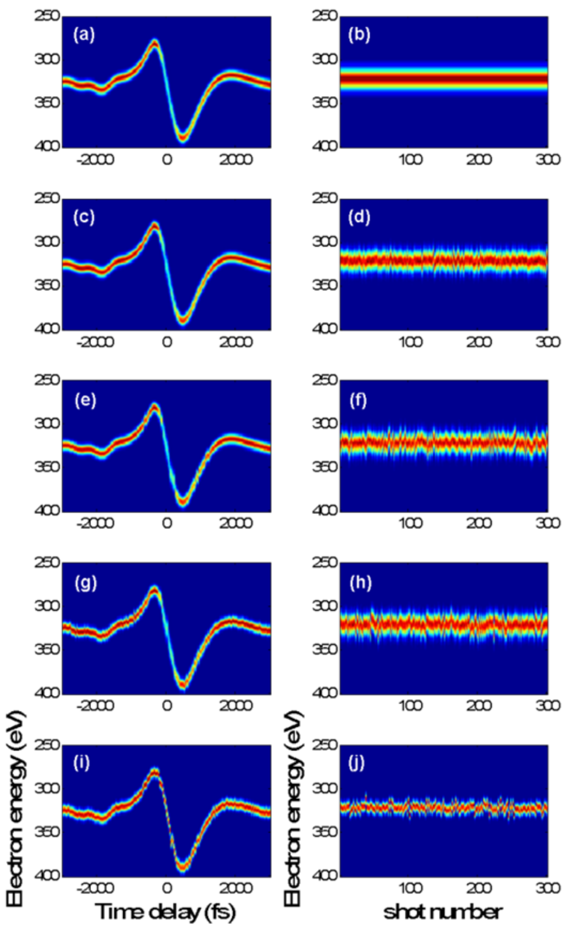


Figure 2: Simulation results of streaking Kr 2p electrons below 2 keV x-ray photon energy by assuming (a) 35 fs, 0 fs time jitter, 0 eV photon jitter, (c) 35 fs, 50 fs time jitter, 0 eV photon jitter, (e) 35 fs, 100 fs time jitter, 0 eV photon jitter, (g) 35 fs, 100 fs time jitter, 5 eV photon jitter, (i) 10 fs, 100 fs time jitter, 5 eV photon jitter; in the right column corresponding shot-to-shot photoelectron spectra are shown with the fixed zero delay.

One can directly see how the streaking trace changes with different x-ray pulse input parameters, and this in turn provides the possibility of reconstruct the x-ray pulse information by recording streaking traces. In principle, the energy jitter contribution can be eliminated from the single-shot spectrometer data and the arrival time of each shot can be determined by mapping the center of mass photoelectron energy into time. Together with the shot-to-shot energy spectral bandwidth and shape, one can calculate the pulse length and profiles in a shot-to-shot basis [10-12].

As mentioned above, an independent photon arrival time monitor based on spectral encoding will also be developed for XFEL.EU. To ensure operation at the high repetition rates in the MHz range, there is a number of issues that have to be studied ranging from fast data acquisition to fast relaxation material, heat load and damage control, as well as MHz white-light generation and characterization [15].

## CONCLUSION

In this paper, potential fundamental shot-to-shot x-ray photon temporal diagnostic methods for XFEL.EU are discussed. The THz streaking and spectral encoding techniques will be implemented in view of the high repetition rate in the MHz range and the high brilliance of XFEL.EU. A laser-based THz generation prototype and simulations of THz streaking of x-ray induced photoelectrons are presented as examples.

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