SIMULATION OF THz STREAK CAMERA PERFORMANCE FOR FEMTOSECOND FEL PULSE LENGTH MEASUREMENT

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Abstract

Extremely bright short-pulsed radiation delivered by the free electron laser (FEL) facilities is used in various fields of science and industry. Most of the experiments carried out using FEL radiation are dependent on the temporal durations of these photon pulses. Monitoring the FEL pulse lengths during these experiments is of particular importance to better understand the measurement results. One of the methods to measure the temporal durations of the FEL pulses is the THz streak camera. This contribution presents simulation of the THz streak camera concept that allows better understanding of the measurement technique and estimating measurement accuracies achievable with this method.

INTRODUCTION

The ultrashort pulses of FEL radiation are used to study the dynamic processes in ultrafast temporal domain. The advancement of the FEL technologies enables delivery of photon pulses with durations in the femtosecond region or shorter. Measuring the lengths of the photon pulses is useful both for the users performing measurements at FEL facilities and the machine operators to monitor the performance of the accelerator itself.

Various techniques are currently used in different facilities to measure the temporal duration of the FEL pulses [1–6]. Among these methods is THz streak camera [2, 7–10] that is able to measure the pulse durations of FEL pulses with photon energies from UV to hard X-ray. To better understand the performance of THz streak cameras, to estimate the possible measurement accuracy of this method and to optimize the data analysis method used to retrieve the pulse lengths from the THz streaking measurements, a Matlab code was developed to simulate the streaking effect and the pulse length calculation procedure. The results delivered by the simulation demonstrate that the THz streak camera method is able to measure the length of the FEL pulses with an accuracy of about a femtosecond and indicate ways towards achieving sub-femtosecond accuracies. More comprehensive information about the simulation procedure and the obtained results is provided in [11].

CONCEPT

The theory of the THz streak camera is presented in detail in [7, 12]. The idea of the method is to encode the temporal duration of an FEL pulse into the energy spectra of the photoelectrons produced by this pulse. This is done by ionizing the electrons in presence of an external THz radiation. Depending on the time of the ionization, the created electron experiences different phase of the THz pulse. Due to the interaction of the electron with the electric field of the THz pulse, its final kinetic energy changes. This change is dependent on the phase of the THz at the moment of the ionization. Electrons created by different parts of a photon pulse have different ionization times and, therefore, experience different energy shifts due to the interaction with the external streaking field. As a result, the energy spectrum of the streaked electrons is the convolution of the non-streaked electron spectrum and the temporal profile of the photon pulse. In case of convolution the rms widths of the two profiles add quadratically, meaning that the spectral width of the streaked photoelectrons can be written in the following form:

$$\sigma_{st}^2 = \sigma_0^2 + \tau_X^2(s^2 \pm 4cs). \quad (1)$$

Here σ_0 is the rms width of the non-streaked spectrum, τ_X is the duration of the ionizing pulse and s is the streaking strength of the THz pulse. The term c in equation 1 represents the linear energy chirp along the photon pulse. The sign $\pm$ corresponds to the electrons traveling along the electric field of the THz and opposite to it. By comparing the two streaked spectra of the electrons to their non-streaked spectra, one can calculate the spectral broadening $\Delta\sigma_\pm$ due to streaking in opposite directions. Using these two amounts of broadening, it is possible to exclude the chirp from equation 1 and obtain the pulse duration as

$$\tau_X = \sqrt{\frac{\Delta\sigma_+^2 + \Delta\sigma_-^2}{2s^2}}. \quad (2)$$

This expression is used in the simulation process to retrieve the rms lengths of FEL pulse using the photoelectron spectra.

SIMULATION PROCEDURE

The simulation procedure uses energy spectra and temporal profiles of different FEL pulses generated by code Genesis [13] to reproduce the ionization of the electrons and their consequent streaking by the THz pulse. Once the non-streaked spectrum and the two streaked spectra of the electrons are obtained, the pulse lengths are calculated using equation 2. The reconstructed rms durations of the pulses are compared to the rms lengths of the input FEL pulses, and the accuracy and the precision of the calculations are estimated for each of the FEL pulses.

Overall, 178 FEL pulses were generated using the Genesis code. The pulse lengths were in range from about 1 fs up to 40 fs. The pulses of lengths from 1 fs to 15 fs were in the hard X-ray radiation range with photon energies of 12.4 keV,

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while the pulses with the lengths from 20 fs to 40 fs were in the soft X-ray region with photon energies of 1.24 keV. The generated FEL pulses corresponded to various operation modes of SwissFEL [14], a free electron laser facility that is currently under commissioning at PSI.

During the simulation the properties of the THz pulse and the electron time-of-flight (eTOF) spectrometers were chosen based on the experimental setup previously used in THz streaking measurements [10, 15, 16]. For such configuration, the main contribution of the uncertainties comes from the measurement accuracy of the eTOFs and from the statistical fluctuations of the electron spectra because of the finite number of the registered photoelectrons.

The simulation procedure assumes that the number of photoelectrons produced by the FEL pulse is proportional to the duration of the pulse. For this reason, different number of electrons are generated in the simulation depending on the length of the input FEL pulses. The electrons are created, and energy values are assigned to them using a Monte Carlo method called acceptance-rejection (rejection sampling) [17]. The energy of a non-streak electron that is measured by the eTOF is given by the following formula:

$$K(t_i) = K_0 + R_n(\sigma_{eTOF}) + ct_i, \qquad (3)$$

where K_0 is defined by subtracting the ionization potential of the electron from the central energy of the photon pulse, c is the linear chirp introduced in equation 1 and t_i is the temporal position of the ionizing photon along the FEL pulse. The function R_n in equation 3 generates random values from a normal distribution with an rms width of σ_{eTOF} . This term in the equation is responsible for the uncertainty caused by the limited resolution of the eTOFs σ_{eTOF}. Using formula 3, a number of electrons is generated that constitute the non-streak spectrum measured by the eTOF. The energy values assigned to the streaked electrons are obtained from the following formula:

$$K_{st}(t_i) = K_{ch}(t_i) + R_n(\sigma_{eTOF}) \pm \sqrt{8U_p K_{ch}(t_i)} sin(\omega_{THz} t_i). \qquad (4)$$

The term $K_{ch}(t_i)$ here is the non-streak energy with the effect of chirp taken into account. The last term of the right-hand-side gives the amount of the energy shift caused by the interaction of the electron with the external THz field, with U_p being the ponderomotive potential and ω_{THz} being the frequency of the THz field.

Once the non-streaked spectrum and the two streaked spectra of the electrons are reconstructed for a certain FEL pulse, the rms duration of this pulse is calculated from the spectral widths using equation 2. The rms widths of the energy spectra are obtained by either fitting Gaussian profiles to them or by calculating directly the rms spread of the simulated spectra. The results of the simulations indicate which of these two methods are preferable for different FEL pulses.

RESULTS

The results provided by the simulations using Gaussian fitting for the spectral width evaluation are shown in table 1 for 10 different photon pulses. The first column shows the photon energy of the FEL pulse, the second one gives the rms length of the input pulses, while the third and the forth columns correspond to the calculated mean pulse lengths with the standard deviations and their absolute accuracies, respectively. One can see from the table that the accuracies

Table 1: Fitting Gausian

Phot. en.	Input len. [fs]	Calc. len. [fs]	Acc. [fs]
12.4 keV	1.5	8.6 ± 3.8	7.1
	1.6	7.9 ± 3.2	6.3
	5.6	6.8 ± 2.2	1.2
	11.3	11.2 ± 1.6	0.1
	16.5	16.9 ± 0.8	0.4
1.24 keV	19.4	20.3 ± 6.4	0.9
	22.2	21.8 ± 5.5	0.4
	26.3	26.1 ± 4.9	0.2
	30.2	31.0 ± 3.4	0.8
	35.8	36.7 ± 3.0	0.9
	39.1	40.3 ± 2.6	1.2

of the calculated average pulse lengths are in range from about 7 fs down to 0.1 fs. For the short pulses, the distribution of the obtained pulse length values has a cutoff at 0, and the average pulse length is shifted towards larger values. For this reason, the obtained average values for the short pulses (about 1.5 fs) serve as a higher limit estimate of the pulse lengths. As for the pulses longer than 5 fs, the accuracies are about 1 fs or better. The accuracy gets worse for the longer pulses as they correspond to photoelectron energy spectra that are not perfectly Gaussian (more flat-top), and the fitting process induces additional uncertainties. The standard deviations of the calculated pulse lengths per input pulse (precision of the calculation) vary from about 6 fs down to sub-femtosecond. The precision of the measurements improves with longer pulse lengths as they correspond to a larger number of measured photoelectrons and, therefore, smaller statistical fluctuations of the energy spectra. Table 1 also shows that the precision is better in case of the hard X-ray FEL pulses. This is caused by the fact that the higher photon energies correspond to more energetic photoelectrons that are streaked more by the THz field (equation 4). This corresponds to a bigger value of the streaking strength s from equation 2, which reduces the uncertainties in the pulse length calculation.

The results obtained by using the direct rms widths of the spectral distributions are shown in table 2. Similar to the Gaussian fitting method, the values obtained for the short pulses in this case show only the upper limit of the lengths. Meanwhile, the average pulse lengths calculated for the FEL pulses of 5 fs and longer, have accuracies of sub-femtosecond. The precision of the calculations is in range from 4.8 fs down to 0.6 fs and improves with longer photon pulses and higher photon energies. Comparing the results presented in tables 1 and 2, one can see that in average the

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Table 2: Calculating rms Widths

Phot. en.	Input len. [fs]	Calc. len. [fs]	Acc. [fs]
12.4 keV	1.5	6.1 ± 3.1	4.6
	1.6	6.4 ± 2.6	4.8
	5.6	6.2 ± 2.2	0.6
	11.3	11.1 ± 1.1	0.2
	16.5	16.5 ± 0.6	<0.1
1.24 keV	19.4	19.1 ± 4.8	0.3
	22.2	21.7 ± 4.0	0.5
	26.3	26.3 ± 2.7	<0.1
	30.2	30.1 ± 2.2	0.1
	35.8	35.8 ± 1.8	<0.1
	39.1	39.2 ± 1.8	0.1

second calculation method provides slightly better accuracy and precision. Such a result is caused by the fact that the calculations using the Gaussian fitting method include additional uncertainties caused by the fitting process.

CONCLUSION

A number of simulations have been performed to better understand the performance of the THz streak camera photon pulse length measurement method. The simulations are based on an experimental setup used for streaking measurements. During the pulse length calculation two different methods of evaluating the spectral widths have been tested. The results revealed that the direct calculation of the rms spread of the simulated energy spectra corresponds to better accuracy and precision. The simulation results showed that the THz streak camera technique is capable of measuring the duration of FEL pulses with accuracies of about 1 fs both in soft X-ray and hard X-ray regions.

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