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Single-shot temporal characterization with the transverse deflecting structure PolariX and THz streaking at FLASH

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Abstract. At the free electron laser FLASH at DESY pulse length measurements can be performed with e.g. THz streaking or an analysis using the PolariX TDS. Since THz streaking examines the XUV pulse directly whereas the PolariX TDS focuses on the energy distribution of the (XUV pulse generating) electron bunch, both techniques are capable of analyzing the same XUV pulse simultaneously. We used a newly installed laser heater to shape the electron bunch and therefore influence the XUV pulse profile and compare the resulting pulse shapes measured by THz streaking and the PolariX TDS. We compare average pulse profiles as well as single-shot examples and discuss the challenges of both types of analysis.

1 Introduction

Free electron lasers (FELs) play an important role across diverse scientific disciplines. Still, experiments benefit significantly from non-destructive online photon diagnostics of the delivered XUV pulses. In particular, determining the pulse duration has proven challenging. Insights into the longitudinal pulse profile can be gained by direct photon-based diagnostics or indirectly by analyzing the energy distribution of the electron bunch after it passed the undulator. For the former a THz streaking method [1, 2] can be applied, where the XUV pulse profile is measured by mapping its temporal structure to the kinetic energy distribution of photoelectrons. The latter can be achieved by using a Polarizable X-Band Transverse Deflection Structure (PolariX TDS) [3, 4], which enables the measurement of the longitudinal phase space of the electron bunch, in combination with a magnet that acts as an energy spectrometer. For the first time at FLASH, reconstructed XUV pulse shapes from both TDS analysis and THz streaking are compared. For this comparison we used a FEL setup delivering double pulses. In addition, we were able to influence the electron distribution with a laser heater [5, 6] in order to suppress the FEL lasing process in some parts of the electron bunch [7, 8].

1.1 Methodology and data analysis

To carry out a photon pulse profile reconstruction utilizing a TDS, the electron bunch energy distribution is compared to the energy distribution without lasing. Comparing the current distributions from lasing-on data and lasing-off references isolates the FEL lasing effects. The difference in the center of mass (COM) or the energy spread (RMS) can be compared [9] in order to reconstruct the XUV pulse shape. Lasing-off references are typically recorded by detuning a corrector magnet upstream of the first undulator, which forces the electron bunch on a path that does not overlap with the photon beam sufficiently to lead to a lasing process. Ideally, this detuning minimally alters the electron path, preserving the initial distribution. In particular the current profile should not change. In reality, the slightly different electron path through the undulators sometimes lead to a different electron distribution and different current profiles. These effects have to be investigated in more detail in the future. For an accurate pulse profile it is required to have a lasing-off reference with a phase space similar to the lasing-on data, aside from the FEL lasing effects. Also, it is critical to correctly match the time and energy axes of the lasing image and the reference. In our work we find the reference the same way as described in reference [10], which uses a hierarchical clustering method (AgglomerativeClustering from sklearn) to group similar electron current profiles and use the Pearson correlation coefficient to identify the best match between lasing-on current profiles and lasing-off group averages. For aligning time axes, one of two methods is usually applied: interpolation of the signal region to a defined number of slices (as in ref. [10]) or overlapping the centers of mass of the electron bunches. Energy axis alignment, affected by jitter and drift, often involves adjusting y-positions so that the integrated XUV pulse profiles match with independent pulse energy measurements using a gas monitor detector (GMD) [11]. We instead set a non-lasing region of the pulse profiles to zero, gaining useful insights from data even when the signal surpasses the fluorescent screen's energy range.

In the THz streaking setup, the FEL XUV pulse ionizes a noble gas target leading to a photoelectron distribution with the same temporal shape. When the ionization region is superimposed with the electric field of a THz pulse, the temporal structure of the XUV pulse is mapped into kinetic energies of the photoelectrons, as long as the electron bunch is significantly shorter than the period length of the Terahertz field [1, 2]. The electron kinetic energy distribution is recorded by electron time-of-flight (eTOF) detectors. The setup used was installed at the beamline FL21 and is described in detail in the reference [12]. Depending on the time window of interest, we used different ramps of the THz streaking field. Here we can choose between a large time window with low temporal resolution of a short window with better resolution. Extracting the correct pulse shape with this method can be challenging; however, a complete absence of a photoelectron signal during a specific time window unambiguously indicates that no XUV pulse was present at that time.

1.2 Comparison of pulse profiles from THz streaking and TDS analysis

We compare XUV pulse profiles from three different FEL setups. Here, we focus on comparing the reconstructed XUV pulse shape, specifically addressing whether one or two XUV pulses are present. Different electron bunch and XUV pulse characteristics are achieved by changing the set undulator wavelength and by modifying the electron bunch with the laser heater. With increasing intensity, the laser heater initially enhances the FEL lasing process by suppressing the accelerator microbunching instabilities. As the intensity increases further, however, it hinders the FEL lasing process by increasing the initial energy spread, a phenomenon also referred to as 'overheating' of the electron bunch [8]. To create distinct temporal features for the comparison, we used a beam setup with a non linear compression to obtain an electron bunch with two current spikes. The TDS images and current profiles of one example each of lasing-on and lasing-off from each of our three setups are depicted in Figure 1. For all three setups, two current spikes are clearly visible, whereas it is important to remember that a high current does not automatically correspond to an XUV pulse, especially for large energy chirps. We collected approximately 3000 lasing-on samples and around 2000 lasing-off samples for each dataset. For all setups the electron beam energy was 965 MeV.

The resulting pulse shapes for the TDS and THz streaking analysis for all three setups are depicted in Figure 2. In setup1 the undulator was set to deliver an XUV wavelength of 11 nm. The laser heater was attenuated just enough to maximize the FEL lasing intensity, resulting in a XUV pulse energy of approximately 140 μJ. The different ratios of the current spikes at 0 fs and 320 fs indicate that (probably due to a too much altered electron trajectory) we do not have well-matched lasing-off references. Com-

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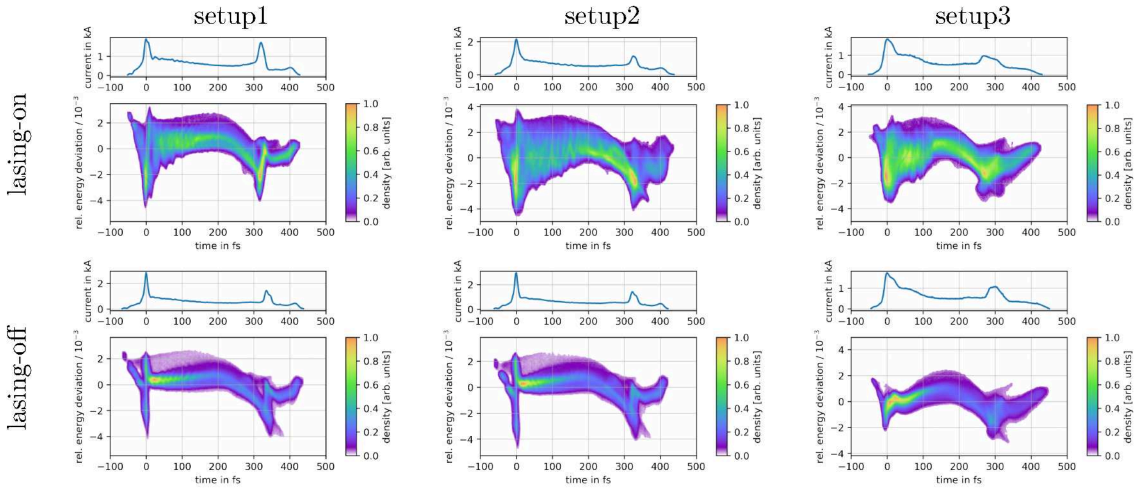


Figure 1: One example of TDS images and their corresponding current profiles of lasing-on and lasing-off for each setup. From setup1 to setup2 we increased the undulator wavelength, from setup2 to setup3 we applied overheating with the laser heater. Each setup clearly shows two current spikes with a time gap of approximately 320 fs. The time zero is defined as the center of the larger current spike, the head of the electron bunch is on the right. All images have individual color-code intensity scales.

parison of the current profiles of the entire lasing-on and lasing-off datasets (not shown here) reveals that the arrival time differences between the two current spikes vary but are, on average, about 20 fs larger for the lasing-off data. In an attempt to account for these effects, we adjust the time axis such that the current spikes overlap rather than simply matching the entire signal region. However, this does not give us a perfect reference, which limits the accuracy of our results. When we compare the COM and RMS profiles of setup1 in Figure 2, which should be identical, we find that the shapes differ significantly around 320 fs (at the position of the second current spike). We even observe a negative signal. This strongly indicates a not matching reference, and problems to reconstruct the shape of this part of the pulse. Here we can compare to the direct measurement of the XUV pulses by THz streaking. Due to the relatively large influence of the eTOF spectrometer instrument function, THz streaking analysis has a limited temporal resolution for reconstructing of the exact pulse shape. However, the fact that no photoelectrons are measured in the region of the second current peak around 320,fs for setup1 (Figure 2 setup1), combined with the ability of THz streaking to detect and resolve such peaks (Figure 2 setup2), provides clear evidence against the existence of a second XUV pulse.
For the next setup (setup2) the undulator wavelength was set to 17 nm (without changing the accelerator settings). Here we obtain a mean FEL pulse energy of $\sim 280\,\mu$J and the lasing-on data of Figure 1 setup2 shows an increased energy spread compared to the lasing-on of setup1. For this setup, the current profiles of lasing-off and lasing-on are in good agreement, and the different matching approaches described above do not lead to different profiles. Both the COM and RMS method indicate the presence of two XUV pulses. In order to cover a time span of approximately 400 fs with THz streaking, a streaking setting with a long THz ramp had to be used. The smaller time window streaking setting used for setup 1 and 3 clearly detects the 2 pulses but due to the short THz ramp lengths the temporal axis is strongly nonlinear. To avoid this artifact we used a longer ramp leading to a much larger influence of the spectrometer resolution as previously reported [13]. Due to the resolution limit we could not determine the rather short pulse duration of the individual pulses with the THz streaking. However, the distances and intensity of both XUV pulses align with the TDS measurements. To enable direct comparison of the XUV pulse shape reconstructed by THz streaking to the TDS measurements, we convoluted the XUV pulse shapes reconstructed from the TDS images with the THz streaking instrument function (namely the photoelectron spectrum without THz streaking field). The convoluted pulse profile obtained from the TDS COM method aligns closely with the predicted pulse profiles from the THz streaking measurements. For the TDS RMS analysis, the pulse intensity of the smaller XUV pulse is underestimated in comparison

to the THz streaking results. Notably, for this setup, where we have a reliable reference, both methods agree with the THz streaking measurements in identifying a second pulse.
In the third setup we aim to eliminate the weaker XUV pulse using the laser heater by setting its intensity to maximum and therefore overheat the electron bunch (setup3). This leads to a reduction of the average XUV pulse energy to around 90 μJ. As we have some TDS reconstructions where parts of the reconstructed pulse profiles are negative, we exclude examples with a minimum of the pulse profiles less than -0.1 GW of the further evaluation. This is again due to a missing reference and excludes about 80% of the dataset obtained from the TDS measurements. The COM and RMS method of the TDS analysis both suggest some minor signal in a second XUV pulse, showing the limitations of the TDS reconstruction for complex electron pulse shapes, but they do not agree or show a distinctly pronounced second peak. In contrast, the THz streaking analysis clearly indicates the absence of a second pulse. This shows that we have succeeded in eliminating the weaker XUV pulse using the laser heater. The wrongly predicted signal of the TDS analysis appears in a region where the electron bunch chirp changes rapidly (at around 320 fs in Figure 1), and we also observe strong variations of low energy electron densities, which results in artifacts in the TDS analysis.

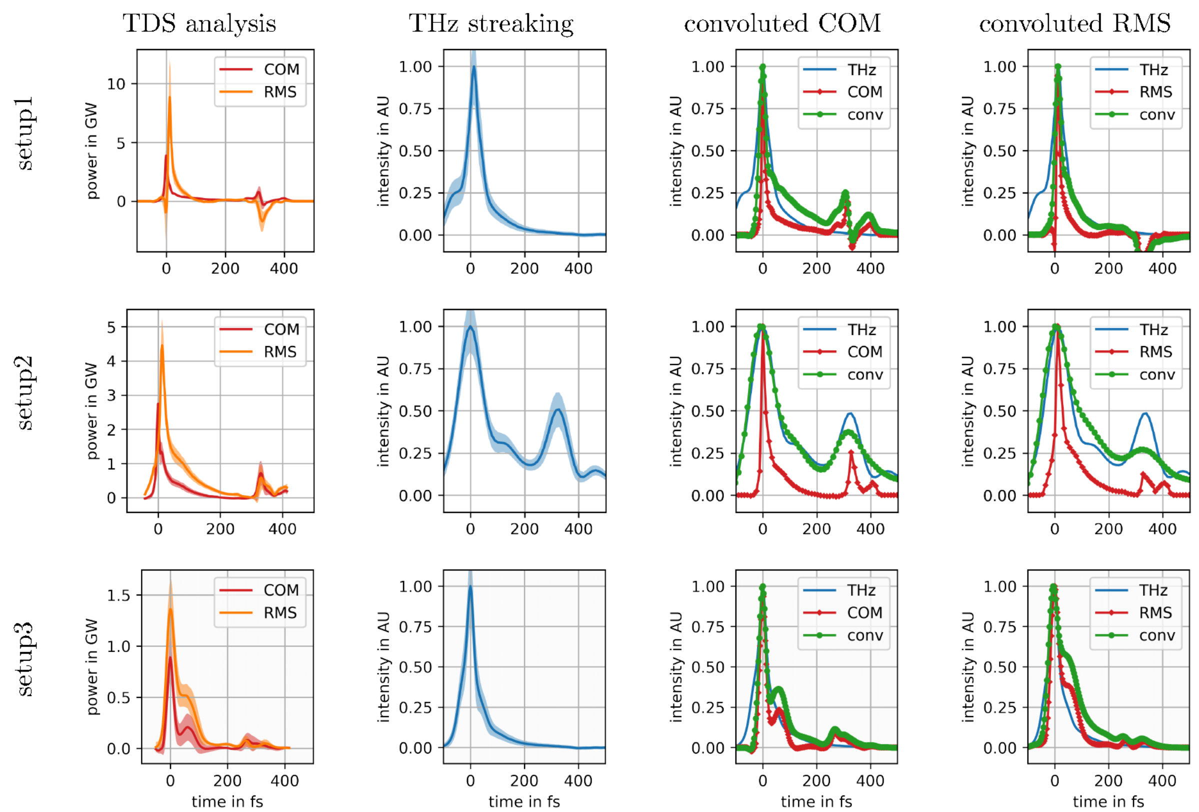
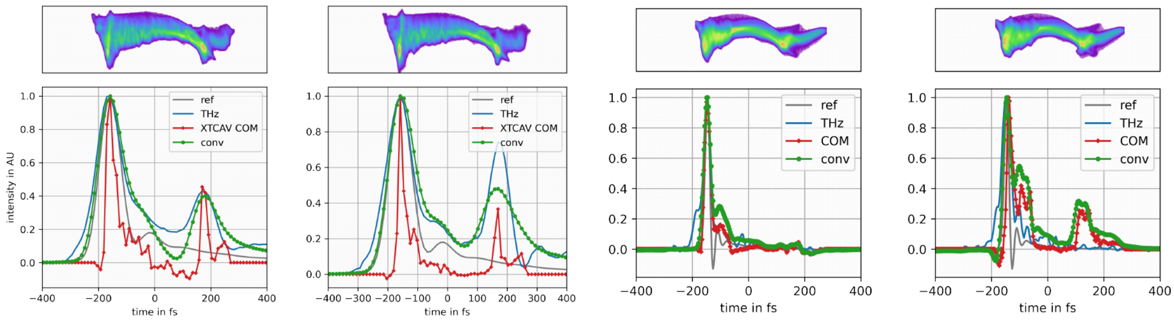


Figure 2: Comparison of XUV pulse shapes from TDS analysis (COM and RMS method) and THz streaking for setups $1-3$. Solid lines are averaged values, shaded areas indicate the standard deviation. The green 'conv' profiles show the respective TDS profiles convoluted with the THz instrument function and hence should ideally agree with the measured THz streaking results. For setup1 COM and RMS profiles differ for the prediction of a second peak around 320 fs, whereas THz steaking results clearly show no photon intensity at this position. For setup2 COM and RMS are in good agreement and all methods predict a second pulse. For setup3 we see different profiles for COM and RMS again, however both indicate that there is no large second pulse. From THz streaking it is clear that no second pulse is present.

1.2.1 Single-shot evaluation

Both methods, TDS analysis and THz streaking can be used for single-shot analysis. Since the PolariX TDS is positioned downstream of the undulator, both methods can evaluate data from the same electron bunch / XUV pulse. For the single-shot pulse profiles, examples illustrating both good and poor agreements are depicted in Figure 3. For profiles of setup2 the relative pulse intensities measured by THz streaking and the TDS reconstruction do not match well in all examples. The TDS COM analysis tends to predict lower intensities for the weaker, pulse (at around 200 fs in Figure 3). However, the TDS analysis remains consistent in predicting a second XUV pulse.
In the TDS profiles from setup3 some individual examples show a second, pronounced pulse. This might be connected to strong fluctuations in electron energies in this region, most likely induced by the laser heater. Since the reference matching algorithm does not specifically focus on this small part of the electron bunch, the assigned reference might not be sufficiently accurate.



(a) setup2, good agreement
(b) setup2, inaccurate pulse intensity ratio
(c) setup3, good agreement
(d) setup3, additional pulse

Figure 3: Four single-shot examples. Here, time zero is defined as the horizontal center of mass of the TDS image. The THz streaking curves are shifted accordingly. 'ref' is the the photoelectron spectrum without THz streaking field and is convoluted with the TDS profiles to compare both curves with a similar resolution (conv). We see two examples where the methods agree well (a,c), and two where we get an artefact in the analysis (b,d).

1.3 Conclusion

We have compared the results of reconstructed XUV photon pulse profiles obtained with TDS analysis, based on longitudinal phase space measurements of the electron bunch, with pulse profiles obtained by THz streaking, based on photo-ionization by the FEL XUV pulse. Whereas measuring the longitudinal phase space with a TDS is relatively straightforward, obtaining the XUV pulse profiles can be challenging, particularly for complex phase spaces. When the resulting pulse profiles of the center of mass (COM) and root mean square (RMS) TDS analyzing methods align, information regarding the temporal XUV pulse structure can be considered reliable, although small features in the regions of strongly varying energy chirp and/or strong laser heater regions can be falsely predicted. While the TDS analysis provides detailed pulse shape information with high temporal resolution, in the order of few fs, our THz streaking method measures directly the (general) XUV intensity and hence can facilitate interpretation of pulse shape features, especially when discrepancies arise between COM and RMS results. On the other hand, the absence of photoelectrons in a specific time window can clearly confirm that no XUV signal was present during this period. By combining TDS with THz streaking techniques, we have successfully demonstrated that we could utilize the laser heater to shape the electron bunch and effectively suppress one of two XUV pulses.
Monitoring lasing-off current profiles throughout the measurement is crucial for managing drift effects and in order to ensure that the reference method does not alter the electron trajectory too much. In case of strong overheating a single-shot analysis with the TDS might not be sufficiently accurate. Inaccurate second pulse predictions from PolariX TDS for some single-shots highlight the need for careful analysis given the uncertainties inherent in both methods.

1.4 Acknowledgement

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