Single-shot temporal characterization of soft X-ray SASE FEL radiation by terahertz field driven streaking

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Abstract: We report about the commissioning of a terahertz (THz) field driven streak camera delivering the pulse duration and the arrival time information with around 10 fs resolution for each single XUV FEL pulse at FLASH. Pulse durations between 300 fs and <20 fs have been measured for different FLASH FEL settings. In particular the arrival time analysis showed the precision with which FLASH can be operated meanwhile. The pulse duration was measured together with several other pulse parameters (spectrum, pulse energy, electron bunch duration) allowing an almost complete characterization of the XUV pulses. In addition we have the unique possibility to investigate correlations between different parameters on a shot to shot basis.

Since the free-electron laser FLASH at DESY in Hamburg, Germany [1] lases in Self-Amplified Spontaneous Emission (SASE) mode each pulse is “unique” and has different pulse energy, XUV spectrum and pulse duration. Due to very small fluctuations in the acceleration, the arrival time of the XUV pulses jitters within several tens of femtoseconds. The focus of online diagnostics at FLASH is to measure all fluctuating properties as completely as possible. Due to the burst mode structure of FLASH with up to 800 pulses spaced by one microsecond (at a repetition rate of 10 Hz) such measurements are a challenge.

A number of methods have been developed and are in use to determine pulse energy [2], spectrum [3,4] and arrival time of the electron bunches [5], while the XUV pulse duration still lacks a suitable detector. Providing sufficient pulse length information will aid precise analysis of measurements of nonlinear interactions as well as pump-probe experiments that make use of the short pulse length.

A THz streak camera [6,7] has the potential to deliver single-shot pulse duration information basically wavelength independent and with a high dynamic range (in pulse duration and FEL energy) and it is able to be operated with repetition rates up to several hundred kHz (potentially even MHz). In addition, it can provide arrival time information between the XUV pulse and the laser driving the THz generation for each single pulse with accuracy well below 10 fs resolution. Due to its wide working range the concept can not only be used for FLASH, but also for EuropeanXFEL or other X-ray FELs [8].

The measurement principle is based on a noble gas target being photo-ionized by the FEL pulse. The kinetic energy of the resulting electrons is modified by the electric field of the THz radiation, when it is co-propagating through the target. If the electron wave packet is short compared to the period length of the terahertz field (> 500 fs in our case), the temporal structure of the wave packet will be mapped onto the kinetic energy distribution of the emitted electrons [9]. The pulse duration can be extracted from the broadening of the peaks measured in the photoelectron spectrum due to the presence of the THz field. The shift of the kinetic energy peaks provides the arrival time.

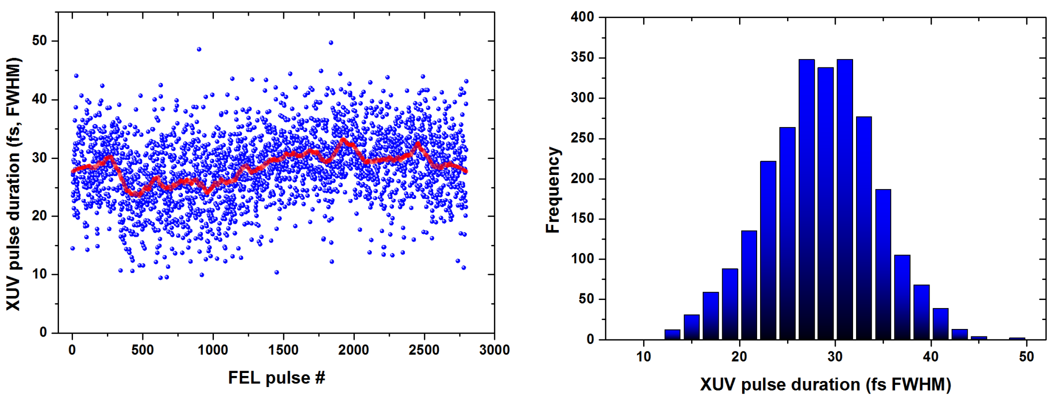

Figure 1. Single shot pulse duration for around three thousand FLASH shots. The red line indicates the mean value of ~30fs. Error bars (not shown) due to the fit uncertainty are on the order of 20%. On right is shown histogram of the measured pulse durations.

The THz streak camera was build and installed at FLASH at the PG0 beamline. This beamline has the capability to use the zero order FEL beam for the streaking set up while the dispersed radiation can be simultaneously used in the PG2 monochromatic beamline to measure the FEL spectrum with high resolution. The THz radiation is generated by interaction of pulses delivered from the FLASH1 pump-probe laser (800 nm, ~70 fs, 6.5 mJ) with a nonlinearly reacting crystal. In detail, the source is based on pulse front tilt optical rectification in a Lithium niobate (LiNbO3) crystal [10]. A THz field strength up to 300 kV/cm has been reached in the interaction point.

Several different FEL operation settings have been used to commission the technique in a wide range of pulse durations from 200 fs to less than 20 fs (FWHM). For each setting the FLASH single-shot pulse duration as well as the arrival time of the XUV pulses with respect to the THz generating optical laser was measured. As one example for the measurements, a time sequence of 5 minutes (3000 pulses) is given in Fig. 1. It shows the inherent fluctuations of the pulse duration. Thus, analysis of user experiments can be improved significantly once this information will be available online for each FEL pulse.

As a second important result of the commissioning experiments, we could verify the assumption that the electron beam arrival time monitor (BAM) measuring the arrival time of the electron bunches with high precision in the FLASH accelerator is an acceptable measure for the arrival time of the XUV photon pulses in all measured cases [11]. The arrival time of the electrons determined almost 200 meters upstream of the experimental hall in the accelerator tunnel (with respect to the FEL master timing) is in good agreement with the arrival time of the XUV pulses with respect to the pump-probe laser (generating the THz and also synchronized to the master timing) at the experiment. As presented in Fig. 2, the shot-to-shot arrival time measurement shows a correlation width of 20 fs rms or less for most of the settings investigated so far. Thus, the time resolution of user pump-probe experiments (using the pump-probe laser) can be significantly improved by sorting their data with the arrival times measured by the BAM. Single-shot pulse duration measurements of XUV pulses covering the full range of <20 fs to 200 fs have been demonstrated. In addition, very good agreement between the electron beam arrival time monitor (BAM) data and the actual arrival time fluctuations of the pump-probe laser at the experimental endstations was verified.

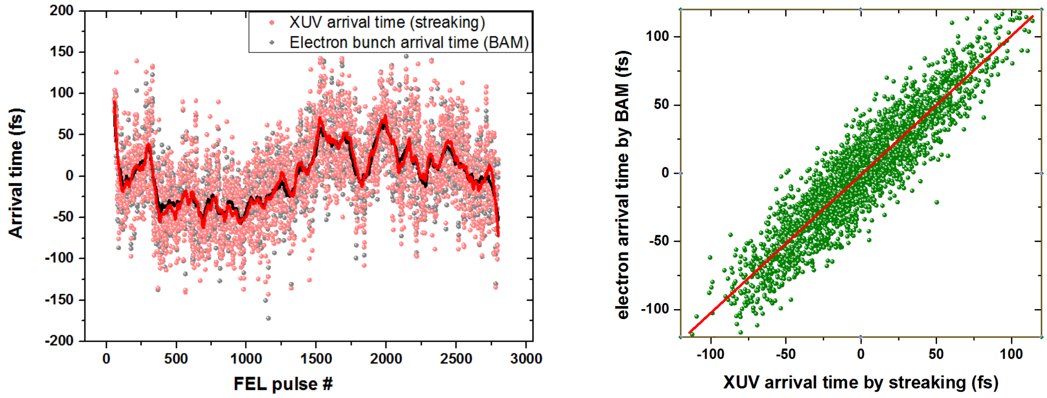

Figure 2. The arrival time is plotted (left) for the same FEL pulses as in Fig. 2. XUV (red) and electron (black) arrival times agree well on a shot-to-shot basis (dots). Averaging the arrival time over 10 seconds (lines) still provides a very good agreement. The correlation plot (right) comparing the arrival time measured for electrons in the accelerator using a BAM and the XUV pulses at the experiment (streaking) shows a correlation width of only 20fs rms. The red line indicates the linear fit.

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