The pump-probe facility:
An optical laser system synchronized to the FEL

S. Düsterer, H. Redlin, A. Azima, F. van den Berghe, H. Schlarb, S. Kapitzki, E. Plönjes-Palm

The VUV FEL is a unique source for extremely bright and short – indeed ultra short – light pulses. Among other applications, these short pulses can be used to explore the temporal evolution of various processes happening on the femto- and picosecond time scale, like atomic motion, phase transitions, hot plasma expansion and many more.

To measure events happening on such short time scales, the so called pump-probe technique is mainly utilized. Two short pulses are required: One - the pump-pulse - initiates a reaction while the second - the probe pulse, arriving at a defined later time - “looks” at the state the system under investigation evolved to after initiation by the first one. These two pulses could both be originating from the FEL itself. Several ideas along that direction are pursued and options for such experiments will be available in the future. A much more flexible approach, however, is to use one FEL pulse and a second, ultra-short pulse in the optical frequency range. With an optical laser pulse, it is much easier to change the wavelength, the polarization, angle of incidence, or delay the pulse from the fs range up to several nanoseconds. Such an ultra-short laser-pulse source was built in the VUV-FEL experimental hall within the last two years. Exceptional requirements have to be met by this laser system and the associated infrastructure. The laser has to produce ultra-short pulses of ~ 100 fs pulse duration in the same bunch train repetition scheme as the FEL. The system has to be reliable for long term measurements, highly automated, and remotely controllable from the experiment. Pulses have to be guided to 4 different experimental stations. But most of all, the laser pulses have to be synchronized to the FEL pulses - ultimately - within the range of the pulse duration.

The laser that meets the requirements was built by the Max Born institute (Berlin) and integrated into the VUV-FEL user facility in 2004/2005 [1,2]. The approach was to use a modular assembly consisting of three sub systems. The first one, the pump laser, is a copy of the photocathode laser of the FEL. This Nd:YLF based burst mode laser was optimized to produce pulse trains of up to 800 pulses with a spacing of 1 µs between the individual laser pulses. Such bursts can be produced with 2 or 5 Hz. After frequency doubling, green laser pulses (λ=523 nm) with energies of up to 0.6 mJ can be obtained (300 µJ of which are possible to be transported to the experiments). The pulse duration, however, is 12 ps and thus, by more than an order of magnitude, longer than the FEL pulses. I.e. with the 523 nm pulses, the capabilities of the FEL with respect to time resolution in pump-probe measurements can not be utilized fully.

Therefore, a second laser (Ti:Sapphire) is used to produce ultra-short (< 100 fs) but weak (< 3 nJ per pulse) laser pulses. These fs pulses are subsequently amplified using the Nd:YLF laser pulses in an optical parametric amplifier (OPA). As a result we can provide 100 fs short (FWHM) laser pulses at a wavelength of 800 nm and a pulse energy of up to 30 µJ with the burst mode structure of the FEL. The 100 fs pulses as well as the “green” 12 ps pulses are sent to the experiments through a dedicated optical beamline system. Laser pulses from both lasers are synchronized to the reference frequencies (1.3 GHz and 108 MHz) from the master oscillator driving the accelerator. These frequencies are delivered by a 300 m long temperature stabilized cable to the laser hutch. The repetition rate of the fs-laser (108 MHz) is continuously compared to the reference frequencies and if deviations are detected, a control electronics adapts the repetition rate of the laser by changing the cavity length with a piezo.

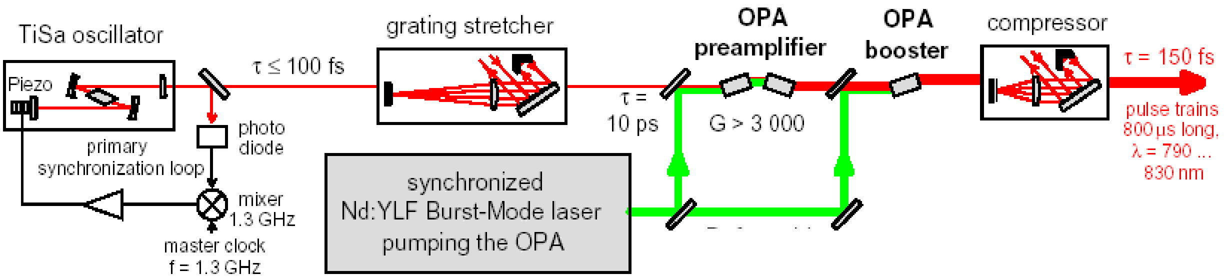

Figure 1: Scheme of the Pump-probe laser system

However, it is even more challenging to measure how precise the synchronization actually is. So far two independent methods to monitor the remaining timing fluctuations (jitter) between the FEL and the optical laser - despite the synchronization - have been developed and installed.

One approach is based on a synchroscan Streak camera (C5680 by Hamamatsu). Part of the laser pulses used for the experiments are reflected to the streak camera as “markers” for the arrival time of the laser pulse. Secondly, a timing reference for the arrival-time of the FEL is needed as well. Here, we use a flash of light which is produced while the electrons, after passing the undulator, are bent into the electron dump at the end of the accelerator (we call it “dipole radiation”). This pulse, which is actually “white” in the optical spectral regime, (all optical wavelengths are present) is as short as the electron bunch (~ 200 fs). It is guided into the laser hutch by a separate 40 m long beamline and focused on the slit of the streak camera. Fig. 2 a shows both pulses on the streak camera. The important information is the relative jitter between both pulses. In order to extract this information for each pulse, the data are fit to a Gaussian function and the peak position is used for further investigation. Fig. 2b presents a 6 hour (45.000 FEL shots) section of a timing stability measurement. The plot shows that the laser follows the FEL quite well (rms of the jitter 800 fs over 6 h). Whereas the largest contribution of the measured jitter actually results from the analysis of the data itself. The peaks of the images on the streak camera can be determined with a resolution of about 300 fs. That is well below the nominal resolution of the streak camera of 2.5 ps.

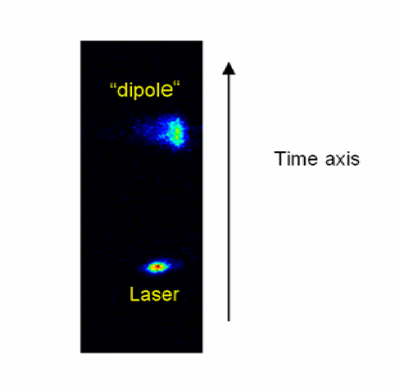

Figure 2a: Image of the laser pulse and the “dipole” pulse as reference for the FEL arrival time on the streak camera . The shown temporal window is ~ 150 ps.

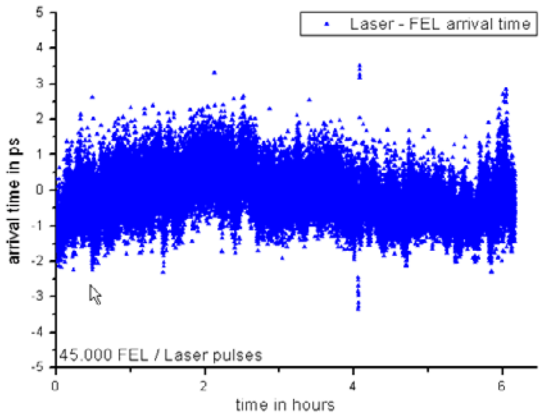

Figure 2b: The measurement shows the temporal deviation from the set value of the two pulses shown in Fig. 2a. 45.000 images (6 hours) like Fig. 2a were analyzed for the graph. The resulting jitter is below 1 ps rms.

In order to enhance the temporal resolution, a second diagnostic experiment was implemented [3,4] to determine the jitter between the optical laser pulses and the electron bunch directly. First results already indicate a better temporal resolution than the streak camera, and a similar experiment at SPPS (SLAC, USA) [5] showed that a sub 50 fs resolution with such a setup is feasible. Some of the optical laser pulses are sent into the accelerator tunnel guided by a glass fibre. Here, the laser is sent through a ZnTe crystal located only a few mm away from the electron beam, within the accelerator beamline. The laser passes through the ZnTe crystal with an angle of incidence of 45°. When the electron bunch comes close to the crystal, its electric field induces a change of the birefringence inside the crystal, thus producing an electro-optical effect. Hence, the experiment was named: Timing Electro Optical sampling (TEO). If the laser pulse reaches the crystal at that moment, when the electron bunch passes the crystal, the polarization of the laser pulse will be turned slightly. Using a polarizer behind the crystal, this phase effect is transformed into an intensity signal, which is monitored by an intensified CCD camera. Due to the mentioned angle of incidence, a mapping of time to space as shown in figure 3a is achieved. Within the resulting time window of about 10 ps, a ~ 700 fs (FWHM) short signal provides the precise timing information about the relative jitter between each optical pump-probe laser bunch and a corresponding FEL pulse (fig. 3b).

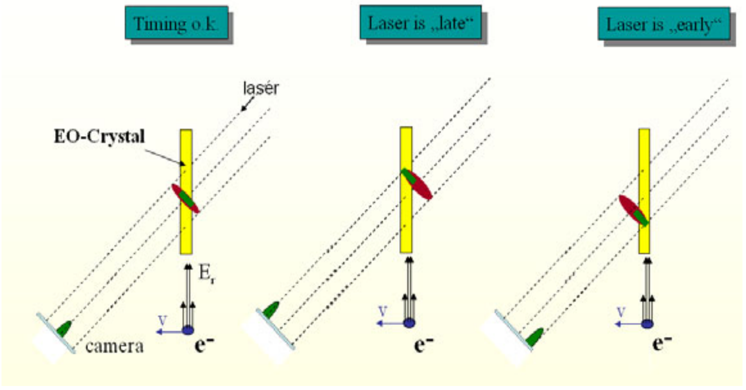

Figure 3a: Scheme of the single shot electro optical sampling. The temporal information is transformed in a spatial intensity modulation.

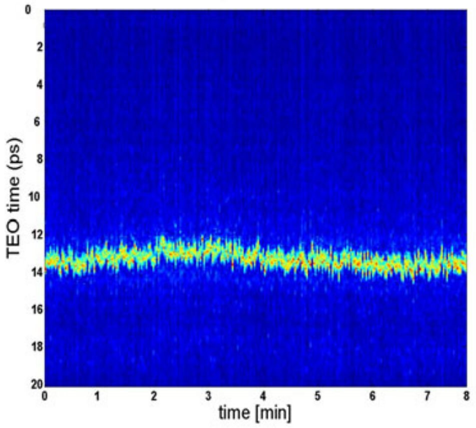

Figure 3b: First measurement results of TEO. The y-axis shows the binned camera image (as indicated in fig. 3a). On the x-axis 1000 successive laser / FEL pulses (~8 min) are plotted. The current time resolution is below 200 fs. Analyzing the shown data a rms jitter of 350 fs was determined

The data gathered by these measurements helps, first of all, to locate noise sources and improve the synchronization. However, some remaining jitter will be still present in the near future. Thus, the recorded jitter-data can also be used by the experiments to sort their measured results after the experiment. In other words, by utilizing the data from the timing measurements, the time resolution of pump-probe experiments is not the jitter anymore, but rather the accuracy of the jitter measurements.

During the first weeks of user operation at the VUV FEL, already 4 pump-probe experiments successfully used of the ultra-fast optical laser pulses synchronized to the FEL for atomic physics, ablation, and nonlinear optical measurements. For the near future, the pulse energy of the laser will be upgraded as well as the pulse duration shortened. Furthermore, the timing measurements and the synchronization need to be improved.

References

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