PRECISION SYNCHRONIZATION OF THE FLASH PHOTOINJECTOR LASER

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Abstract

In this paper we report on the synchronization of the FLASH photo injector laser system to the optical timing reference using an optical cross-correlation scheme. This enables not only the measurement of the laser pulse arrival time on the photo cathode, but also its stabilization using adaptive feed-forward algorithms acting on an electro-optical modulator (EOM) incorporated in the laser's pulse train oscillator. First results from the commissioning and future plans for a feedback system are discussed.

INTRODUCTION

The free-electron laser in Hamburg (FLASH) and the planned European XFEL generate ultra-violet and x-ray pulses with durations in the order of a few 10 fs based on the SASE process. These next-generation light sources require an optical synchronization system [1] to enable user pump-probe experiments with sub-10 fs resolution. Furthermore, in course of the latest FLASH upgrade [2] the laser-driven seeded-FEL experiment (sFLASH) is being commissioned, making a synchronization between an external laser and the electron bunch with a jitter of less than 30 fs mandatory. Taking the also newly installed phase-space linearizing third-harmonic cavity into account, the measurement and control of electron bunch arrival time jitter by means of a complete longitudinal feedback system is even more crucial.

It has been shown [3] that the phase space distribution from the injector strongly depends on the timing between the photo injector laser and the gun. Since changes of the longitudinal properties in the injector affect the longitudinal properties after the final compression of the beam and by that the SASE lasing process, it is evident to have an understanding and a measure of the arrival time of the laser pulses on the photocathode. To accomplish this an optical cross-correlator has been installed during the recent upgrade of the optical synchronization system, being also the prerequisite for the planned RF gun phase feedback.

IMPLEMENTATION

The arrival time of the photo injector laser pulses is measured with respect to the optical timing reference (MLO), as is the electron bunch arrival time (BAM) upstream of the first bunch compressing magnetic chicane. This allows for an achievable resolution of $< 10\,\mathrm{fs}$ [4].

The injector laser system is laid out in a Master-Oscillator Power Amplifier configuration containing an actively mode-locked Nd:YLF pulse train oscillator (PTO), an amplifier stage and a wavelength conversion stage to generate the required high-energy ultra-violet radiation required for the photoemission from the $\mathrm{Cs_2Te}$ cathode. Details can be found in [5], but it should be noted that after the shutdown, FLASH has started operation with an improved version of the discussed drive laser system. The PTO generates $27\,\mathrm{MHz}$ pulse trains of $3\,\mathrm{ms}$ duration at the FLASH macropulse repetition rate of $10\,\mathrm{Hz}$. Approximately 5%, corresponding to a pulse energy of $10\,\mathrm{nJ}$, is tapped off with a pellicle beam splitter and guided to the optical cross-correlator, where another fraction is split off and send to a photodiode to monitor the optical power.

The Master Laser Oscillator is situated in a laboratory in direct vicinity to the injector laser hutch. The reference pulse train generated by the MLO with a repetition rate of $216\,\mathrm{MHz}$ is distributed to various fiber links using free-space optics. These fiber links connect different front-ends, like the bunch arrival time monitors (BAM), to the optical reference [6]. Another fiber transports $\approx 5\,\mathrm{mW}$ of the train into the injector laser hutch, where it is dispersion compensated and boosted to about $70\,\mathrm{mW}$. Thereof two photodiodes ($10\,\mathrm{GHz}$ and $1.5\,\mathrm{GHz}$ bandwidth) are illuminated with $15\,\mathrm{mW}$ for LO generation, amplitude monitoring and polarization control.

Balanced Optical Cross-Correlator

The operation of the balanced optical cross-correlator is based on sum frequency generation (SFG) in a type-I phase-matched BBO crystal. In Fig. 1 the optical set-up

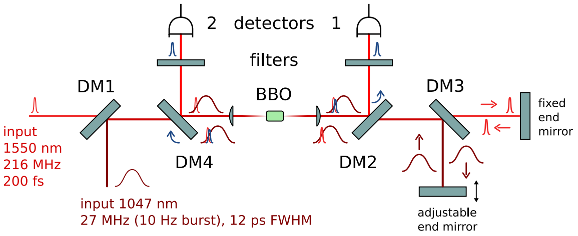

Figure 1: Schematic set-up of the balanced optical cross-correlator. The propagation of the laser pulses is foreshadowed by the arrows.

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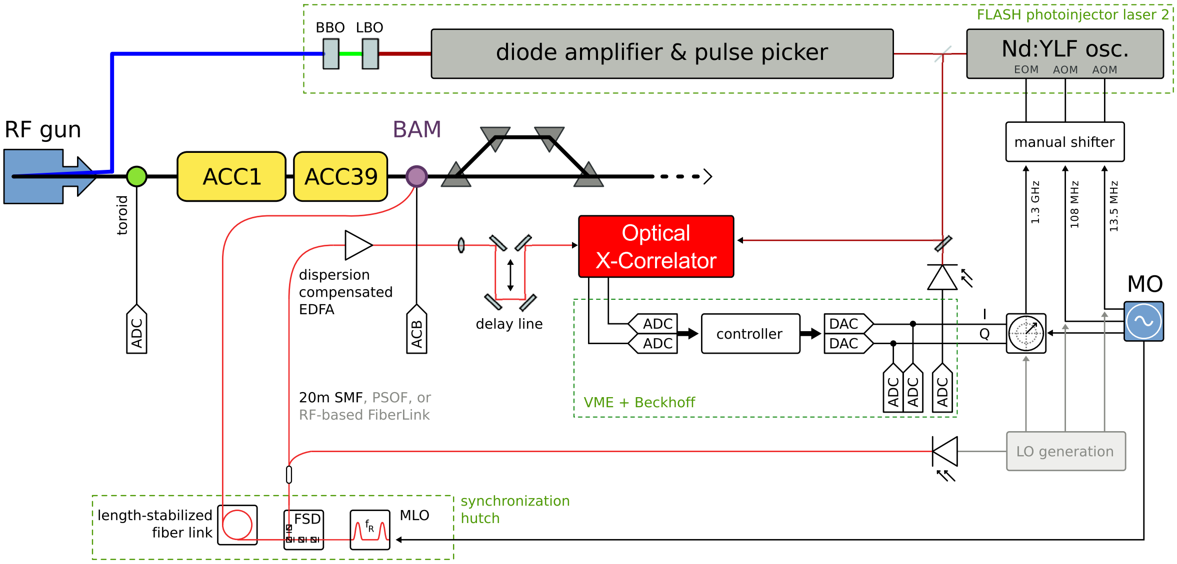

Figure 2: Sketch of the implementation of the optical cross-correlator for injector laser synchronization. The control signal is generated from the PTO and the MLO pulse trains and fed back to the phase of the RF signal driving the EOM inside the PTO's cavity. The electron bunch arrival time monitor upstream of the chicane provides an independent measure.

is shown schematically. The pulse train from the PTO and the amplified reference train enter the device through a first dichroic mirror DM1 before being focussed into the BBO crystal. If both pulses overlap temporally inside the crystal a sum frequency component is generated and propagated to the first detector using another dichroic mirror DM2. The fundamental pulses are seperated again by a third dichroic mirror DM3, temporally adjusted (see below), reflected and combined again. Now they travel in the opposite direction and are focused again into the crystal generating another sum frequency component which, in turn, is coupled out from the beam path by DM4. In front of each detector an optical bandpass filter suppresses strongly the concurrently generated second harmonic components.

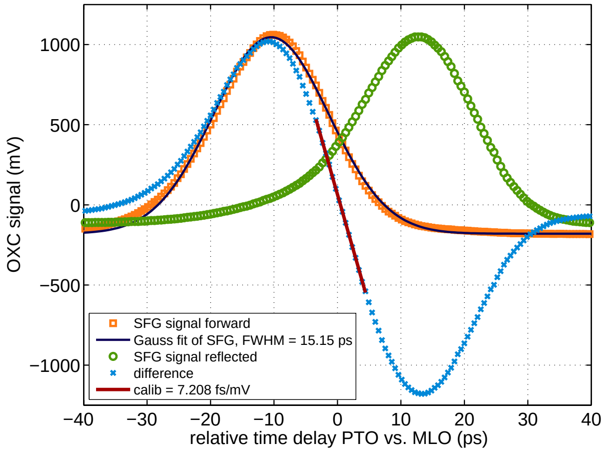

Figure 3: Scan of relative time delay between reference and injector laser pulses.

Measurement and Control

The PTO pulses are long compared to the reference pulses ($\mathcal{O}(14\,\mathrm{ps}) \gg 200\,\mathrm{fs}$ FWHM). The relative timing is adjusted such that the MLO pulse overlaps at one edge of the Gaussian PTO pulse to generate the first SFG component. Using the end mirrors to adjust the delay the second SFG occurs at the opposite edge of the injector laser pulse. Figure 3 shows a scan of the initial delay using a motorized translation stage, where the individual SFG signals (green, orange) is a precise measurement of the PTO's pulse duration. The region around the zero-crossing of difference of the SFG signals is, more importantly, highly sensitive to timing changes between the fundamental pulses. Assuming the amplifier and wavelength conversion stages do not contribute to timing jitter, this difference signal is the arrival time of the pulse train on the photocathode, while at the same time being independent of laser amplitude noise In order to stabilize the arrival time the signal can be used as input of a feedback loop which acts via an IQ (vector) modulator on the phase of the 1.3 GHz RF signal driving the EOM built into the cavity of the PTO (see Fig. 2). Using a feed-forward correction, repetitive arrival time errors across the macropulse can be removed.

MEASUREMENTS

The bunch arrival time monitor installed before the first bunch compressing chicane enables to measure the influence of phase changes of both the injector laser and the RF gun. The electron bunch timing change $\delta t_{\mathrm{bunch}}$ is given by

$$\delta t_{\mathrm{bunch}} = G_{\mathrm{gun}} \cdot \delta t_{\mathrm{gun}} + G_{\mathrm{inj}} \cdot \delta t_{\mathrm{inj}} \qquad (1)$$

where the factors G_i define the fractional part of timing change by the laser and the gun, with $G_{\mathrm{gun}} + G_{\mathrm{inj}} = 1$.

This is equivalent to the fact that timing changes per degree phase change have to add up to 2.14 ps/deg at the accelerating frequency of 1.3 GHz [3]. Figure 4 shows the subsequent scan of the gun phase around its nominal operating point of 0.95 deg and a scan of the injector laser phase using the vector modulator at a fixed gun phase. During the latter measurement the laser pulse arrival time is also measured using the optical cross-correlator signal. To fit the slope, data from 20 macropulses is taken at each setpoint. The sum of absolute values of the slope fits for the electron bunch arrival time amounts to 2.186 ps/deg closely matching the expected value. The slope fit of the laser arrival time data yields to a larger value of 2.35 ps/deg which might be an indication for an imperfect calibration of the cross-correlator. This is supported by the fact that the measured pulse duration of 15.15 ps (see Fig. 3) is also larger than expected.

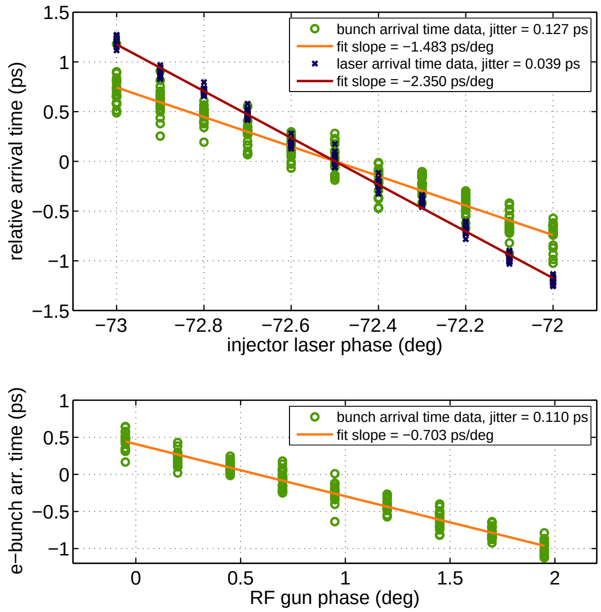

Figure 4: Subsequent RF gun phase and laser phase scans around the nominal operating points.

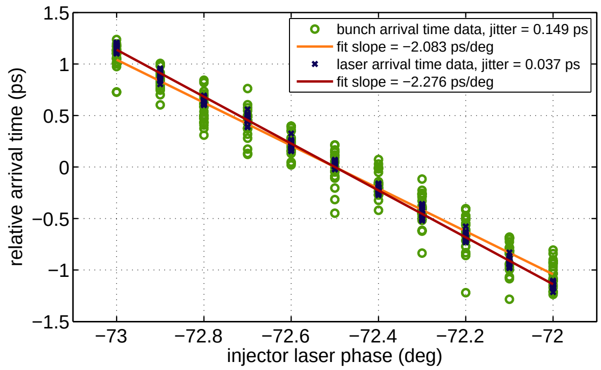

Figure 5: Laser phase ϕ_laser scan at a gun phase setpoint of $\phi_\text{gun} = -18.55$ deg, where the gun does not affect the electron bunch arrival-time.

For the next measurement the gun phase is set to a phase of -18.55 deg, where it the influence on the electron bunch arrival time is strongly suppressed, i.e. $G_\text{gun} \approx 0.05$ determined by a measurement. The arrival time measurement (see Fig. 5) results in slopes of 2.083 ps/deg for the electrons and 2.276 ps/deg for the laser. Hence the laser arrival time jitter is transported by the electron bunch to the BAM. This is an important proof-of-principle experiment for the optical cross-correlator and its relevance for the longitudinal accelerator feedback.

SUMMARY AND FUTURE PLANS

We present first measurements of the injector laser pulse arrival time on the photo cathode and the impact to the electron bunch arrival time upstream of the first magnetic chicane with respect to the optical reference. Although this novel component of the optical synchronization system has only recently being commissioned the results are very consistent with the proven BAM measurement and thus allow for precise laser arrival time measurements up to now.
The immediate next steps include more systematic studies, transfer matrix determination, the implementation of a polarization feedback for the reference pulse train, better integration into the accelerator's control system and a feedback on the delay stage to compensate for drifts which is required to keep the difference of the SFG signals at the zero-crossing. To fully exploit the sub-10 fs resolution of the electron bunch arrival time monitors we are at the same time optimizing the optical setup and the readout electronics of the cross-correlator, since we currently suffer from the signal-to-noise ratio. Long-term measurements and the planned feed-forward and feedback loops require a drift-free and low-jitter connection to the MLO which will be realized using phase-stabilized optical fibers and an RF-based link stabilization scheme.

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