

# COMPARATIVE STUDY OF BUNCH LENGTH AND ARRIVAL TIME MEASUREMENTS AT FLASH

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## Abstract

Diagnostic devices to precisely measure the longitudinal electron beam profile and the bunch arrival time require elaborate new instrumentation techniques. At FLASH, two entirely different methods are used. The bunch profile can be determined with high precision by a transverse deflecting RF structure, but the method is disruptive and does not allow to monitor multiple bunches in a macro-pulse train. It is therefore complemented by two non-disruptive electro-optical devices, called EO and TEO. The EO setup uses a dedicated diagnostic laser synchronized to the machine RF. The longitudinal electron beam profile is encoded in the intensity profile of a chirped laser pulse and analyzed by looking at the spectral composition of the pulse. The second setup, TEO, utilizes the TiSa-based laser system used for pump-probe experiments. Here, the temporal electron shape is encoded into the spatial dimension of the laser pulse by an intersection angle between the laser and the electron beam at the EO-crystal. In this paper, we present a comparative study of bunch length and arrival time measurements performed simultaneously with all three experimental techniques.

## INTRODUCTION

FLASH is a superconductive accelerator at DESY that drives a SASE free electron laser (FEL) operating at VUV wavelength. Because the output power from the SASE process sensitively depends on the bunch peak current produced by compressing the beam in magnetic bunch compressors, several different monitor systems to measure the longitudinal beam profile and its bunch arrival time have been implemented. Measurement of the longitudinal profile is, therefore, a key diagnostic to control the machine performance.

For pump-probe experiments, an external ultra-short pulse laser is used to initiate the physical process that is probed by the VUV-FEL pulse. The evolution of the process is studied by incrementally changing the relative time delay between the laser pulse and the FEL pulse. Timing jitter of the electron bunch with respect to the laser introduces measurement errors. To identify the sources of time jitter, emphasis is put on the development of different measurement techniques that allow for reliable determination of the bunch arrival time, the synchronization accuracy of

the detecting system, and to measure the residual relative timing jitter between the pump-probe laser to the electron beam for off-line correction.

The layout of the facility and the three experimental setups (LOLA, EO and TEO), all operating in the time domain, are shown in Fig. 1. The beam is accelerated in TESLA-like superconducting acceleration modules ACC1 to ACC5. Two magnetic bunch compressors BC2 and BC3 produce longitudinal shorting of the electron beam. Caused by the RF curvature, the electron chirp induced by  $\approx -7^\circ$  off-crest operation of ACC1 causes a non-uniform compression of the electron charge distribution. This results in a short leading spike with high peak current and a long trailing tail.

At the linac exit, an optical beam line allows for transport of an ultra-short laser pulse into the accelerator for electro-optical measurements (EO) [1,2]. The movable electro-optical crystal for our experiment is located sufficiently far away from the beam in order to not compromise the electron beam quality. The experiment can, thus be operated in a parasitic mode while photon FEL beam is delivered to the users.

In the same machine section, a transverse deflecting structure (LOLA) that deflects the beam in vertical direction is installed [3]. The RF phase of the structure is at zero-crossing when bunch is injected. The time varying deflection maps the longitudinal profile into the vertical coordinate and is readout by an imaging screen. The streaked bunch is lost in the downstream collimators. The filling time of the structure is sufficiently short that one bunch in a macro-pulse with 1 MHz bunch spacing can be measured.

The beam passing the collimators through a dogleg reaches the SASE undulator after about 50 m of transport beam line. Upstream of the undulator a second electro-optical setup (TEO) is installed [4]. The laser for TEO is housed in the experimental hutch and is used for pump-probe experiments. The main purpose of TEO experiment is to determine the arrival-time of the electron bunch with respect to the pump-probe laser system. The monitor system allows to sort the experimental data taken by FLASH users according to their pre-recorded arrival times [4].

The interceptive character of LOLA and the order in which the experiments are installed at the FLASH beam line make it impossible to measure the same bunch with all three setups. We, therefore, used adjacent bunches within a macro-pulse train for comparison.

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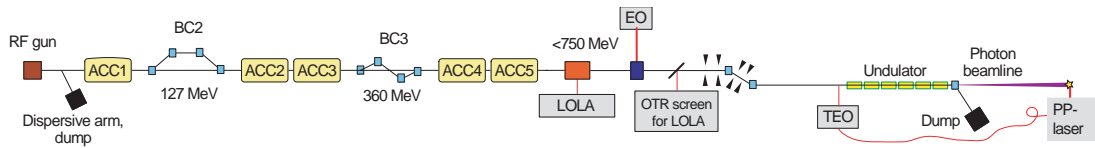


Figure 1: Scheme of FLASH facility. LOLA marks the transverse deflecting structure, EO and TEO the electro-optic experiments operated by dedicated diagnostics laser and the pump-probe laser, respectively.

## MEASUREMENTS WITH TRANSVERSE DEFLECTING STRUCTURE

LOLA is a S-band travelling wave structure operating at a frequency of 2.856 GHz with short RF pulses ( $<1\ \mu\text{s}$ ). The maximum applied deflecting voltage is 20 MV. The bunch image is taken from an off-axis OTR screen mounted 10 m downstream of LOLA. The vertical size of the screen is 17 mm. A horizontal kicker synchronized to the klystron RF pulse is used to steer the streaked bunch onto the screen. In this arrangement, the longitudinal profile measurement can be preformed during SASE operation in a pulse stealing mode. For further details on the setup see [3].

To determine the streak strength with high accuracy the RF phase is scanned by a few degrees around the zero-crossing. Monitoring the vertical beam movement on the screen which is proportional to the phase shift, the calibration, -time versus pixel-, is obtained, where one degree of S-band phase corresponds to 927.6 fs.

The RMS resolution of the longitudinal profile is limited by the vertical beam size (RF off) multiplied by the streak strength. To achieve sub-50 fs FWHM resolution, this usually requires to tightly focus the beam at the screen with suited quadrupoles. Because the measurements in this report were all taken during FLASH user operation, we were not allowed to vary the linac optics. The measurement resolution was therefore limited to 240 fs FWHM.

Figure 2 shows the beam current measured during SASE operation with  $10\ \mu\text{J}$  averaged power at a wavelength of 13.6 nm (682 MeV). The different profiles originated from different power levels feed into the RF structure. The black curve (29.6 fs/px) with the lowest resolution does not re-

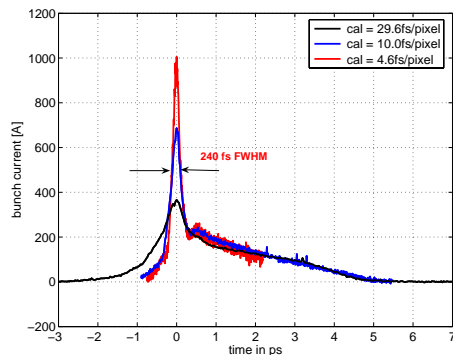


Figure 2: Bunch current measured by LOLA during SASE condition.

flect the sharp leading spike, but allows for a precise calibration. The full size of the CCD image encloses 19 ps measurement range. The blue curve, at 10 fs/px, shows still the entire beam profile including the long trailing tail with 5 ps duration. Since the time axis is plotted, the constant vertical beam size decreases with increasing streak strength and the leading peak gets pronounced. For the red curve with 4.6 fs/px, half of the beam tail is outside of the 17 mm screen. The peak current determined from the profile is 1 kA with a full width duration of 240 fs. Because of the resolution limitations discussed previously, the 1 kA is only a lower limit. The charge carried in the spike is 0.24 nC with 0.8 nC total bunch charge.

## ELECTRO-OPTICS TECHNIQUES

All electro-optical techniques are based on encoding the co-propagating electric field of the electron bunch into the polarization of a broadband optical laser pulse. For that, an electro-optical crystal is installed adjacent to the electron beam. For encoding and decoding, different methods can be used. In the EO setup, spectral decoding[1] and temporal decoding[2] are implemented while the TEO experiment used a spatial decoding technique [4].

The spectral decoding (EO-SD) uses a chirped laser beam where the time profile of the beam is impressed at different wavelength which is then readout by a spectrometer. Due to undesired bandwidth broadening in a short time-slice of the chirped pulse, this method is usually optically limited to 300 fs FWHM and has a small dynamic range (1-3 ps) to achieve this resolution.

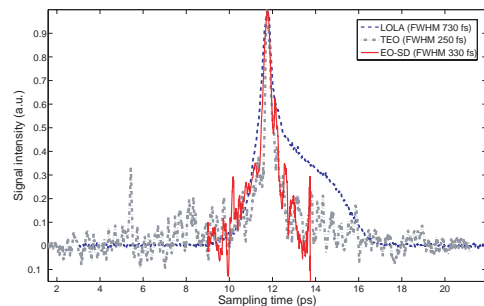


Figure 3: Square of beam profiles measured by spectral decoding (EO-SD) with a not optimized setup, and spatial decoding (TEO). Both use a  $180\ \mu\text{m}$  GaP-crystal. Blue: LOLA with lowest streak (29.6 fs/px).

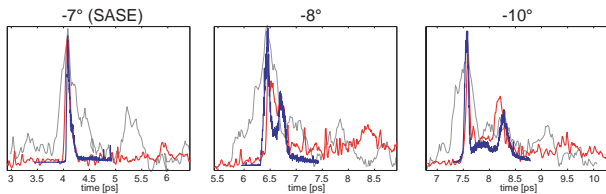


Figure 4: Measurements of the square of the longitudinal beam profiles for different acceleration phases ACC1. Blue: profile obtained by the transverse deflecting structure, red: EO-temporal decoding with GaP (100 $\mu$ m), and light-gray: TEO spatial decoding in ZnTe.

Both other methods are limited by walk-off effects and frequency dependence due to phonon resonance of the EO crystals. The resolution is limited to 200 fs FWHM for ZnTe and 100 fs FWHM for GaP [5].

Laser intensity stability and noise in the readout system required for all three setups to operate the EO-experiment close to, or at a cross-polarizer arrangement, instead of a balanced detection scheme. Hence, the light passing the EO crystal is blocked by a polarizer whose orientation is set orthogonally to the unperturbed laser polarization orientation. The laser intensity variations are proportional to the square of the longitudinal electron beam density. The signal of the long trailing tail due to non-uniform compression is usually within the noise limitation. Profile measurements with LOLA are squared for better comparison.

The signals taken with EO-SD, TEO and LOLA are shown in Fig. 3). Both electro-optic measurements show the sharp spike with widths of 250 fs FWHM for TEO and 330 fs in case of EO-SD. Profiles measured by LOLA are taken at the smallest streak strength (29 fs/px). According to Fig. 2 170 fs is expected for the squared signal. The signal-to-noise ratios of the EO-setups are below 5:1. In both cases, fiber coupling induced fluctuations of intensity or the spectral distribution account for the poor dynamic range. In the TEO setup the laser is transported through a 160 m long fiber and, dispersion compensation elements such as grating stretcher and a SLM which reducing the laser power to at the experiment to few mW.

The highest time resolution so far was achieved using the temporal decoding (EO-TD) technique with a GaP crystal of 100  $\mu$ m thickness [2]. Figure 4 shows the signals from EO-TD, TEO and LOLA for different phase of ACC1. The non-linear compression of the bunch causes fragmentation of the beam head that is accurately reproduced by the EO-TD technique. Features as short as 100-120 fs have been observed.

**Measurement of timing jitter:** It is of interest to compare the timing-jitter of the electron bunch measured by the three methods against each other. For this reason, we have determined the arrival time of the electron bunch by a Gaussian fit on the spike of the EO, TEO and LOLA signal for every bunch. The correlation plots are shown in Fig. 5. Highest correlation is found between EO and LOLA mea-

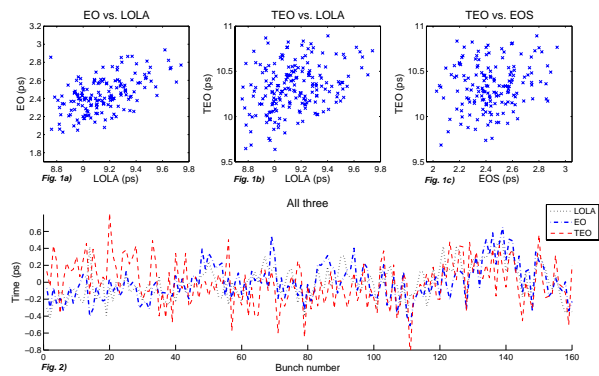


Figure 5: 1 a-c) Correlation plots of the electron bunch arrival time measured by LOLA, EO or TEO. 2) Bunch arrival versus time.

surements, while the correlation between TEO to the others is negligibly small. This indicates, that the pump-probe laser synchronization to the master RF oscillator may contribute considerably to the observed timing jitter. Further studies are required to confirm this observation.

## SUMMARY

The cross-polarizer arrangement used in EO setups makes a direct comparison of the beam profiles observed with a transverse deflecting structure difficult. The complex bunch structure produced by non-uniform compression at FLASH causes a long trailing tail which is not reproduced by EO techniques. Features of the beam head with a resolution of 150 fs FWHM have been observed by temporal decoding in agreement to LOLA measurements. This demonstrates that EO measurements are capable of detecting variations of the peak current or its pulse shape. The fiber transport and the low laser output power at the spatial decoding setup (TEO) is the main reason for a poor signal-to-noises ratio. However, for the determination of the bunch-arrival time, it provides an important tool for the users. Arrival timing correlation measurements indicate that the synchronization between the electron beam and LOLA or the EO-diagnostic laser have a higher accuracy than the one used for pump-probe experiments.

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