

# MEASUREMENTS OF THE TIMING STABILITY AT THE FLASH1 SEEDING EXPERIMENT\*

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## Abstract

For seeding of a free-electron laser, the spatial and temporal overlap of the seed laser pulse and the electron bunch in the modulator is critical. To establish the temporal overlap, the time difference between pulses from the seed laser and spontaneous undulator radiation is reduced to a few picoseconds with a combination of a photomultiplier tube and a streak camera. Finally, for the precise overlap the impact of the seed laser pulses on the electron bunches is observed. In this contribution, we describe the current experimental setup, discuss the techniques applied to establish the temporal overlap and analyze its stability.

## INTRODUCTION

For the operation of an externally seeded free-electron laser (FEL), relative beam-beam jitter between the electron bunch and the laser pulse initiating the FEL gain process is only acceptable to a certain extent. Inhomogeneities in the electron beam slice parameters will directly translate into fluctuating performance of the seeded FEL. The duration of the region of the bunch with suitable electron beam parameters, such as slice energy spread, beam current, and emittance, is limited, which defines the timing jitter budget. Large jitter will naturally result in poor overlap quality. For instance, a major limitation of the studies of direct seeding with an high-harmonic generation (HHG) source at FLASH was the quality of the temporal overlap [1, 2].

## EXPERIMENTAL LAYOUT

### *Electron beamline*

The seeding experiment is installed at the FLASH1 beamline of FLASH [3], the free-electron laser user facility in Hamburg, delivering high-brilliance SASE FEL radiation in the extreme ultra-violet (XUV) and soft x-ray range wavelength ranges. The superconducting linear accelerator of the FLASH facility generates trains of high-brightness electron bunches at a maximum energy of 1.25 GeV. These bunch trains, accelerated at 10 Hz repetition rate, consist of up

to 800 electron bunches at an intra-train repetition rate of 1 MHz.

The seeding experiment is installed between the collimation section of FLASH1 and the FLASH1 main undulator system. The electron beamline, shown schematically in Fig. 1, can be divided into three parts: (i) the modulator section, (ii) the variable-gap undulator system, and (iii) the photon extraction and diagnostics section. Of these, however, only the modulator section was used for the measurements presented in this paper. It comprises two electromagnetic undulators (5 periods of 20 cm, maximum  $K$  value 10.8) that originally had been installed for a longitudinal electron bunch diagnostics experiment [4]. At the exit of each electromagnetic undulator, a magnetic chicane is installed.

Downstream of the seeding experiment, a combination of a transverse-deflecting structure (TDS) and a dipole energy spectrometer is installed. First, an arrival-time-dependent transverse kick is applied in the TDS, an RF structure operated at 2856 MHz. After this conversion of longitudinal to spatial position, the contents of the longitudinal phase space of the electron bunch can be measured on the observation screen in the dispersive section downstream of the energy spectrometer.

### *Laser system*

The laser system used for seeding experiments at FLASH1 was originally installed for direct-HHG seeding experiments at FLASH and consists of a 108.3 MHz Ti:sapphire oscillator used as seed in a classical chirped pulse amplification (CPA) scheme with 35 mJ maximum pulse energy at 35 fs FWHM minimal pulse duration. As described in the following section, the oscillator is electronically synchronized to a reference signal derived from an optical reference. The amplifier is pumped by a frequency-doubled Nd:YAG laser operating at 10 Hz allowing to seed one electron bunch per train [5].

For high-gain harmonic generation (HHG) seeding at short wavelengths, a conversion of the  $\lambda = 800$  nm laser pulses to UV wavelengths is required. For this, an in-vacuum arrangement of two non-linear optical crystals in the accelerator tunnel is employed: While the first one converts the laser light into its second harmonic, the second one emits its third harmonic at 267 nm when overlapping the 800 nm and 400 nm pulses [6].

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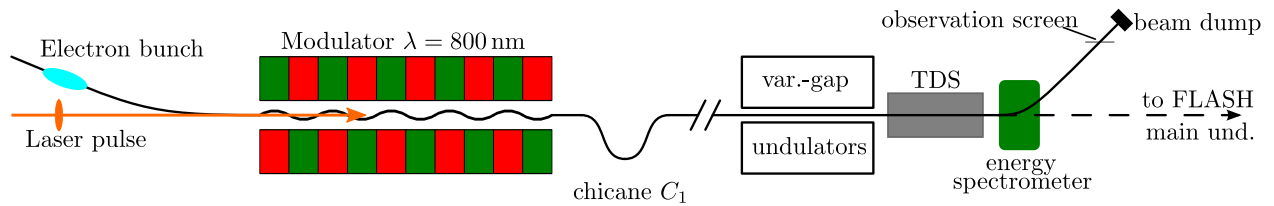


Figure 1: Layout of the hardware used in these measurements. The electron bunches arrive from the energy collimator of FLASH1, the seed laser pulses are injected into the accelerator vacuum upstream of the last dipole of the energy collimator. After modulation, the electron bunches are density-modulated in chicane  $C_1$ . Finally, the longitudinal phase space of the electron bunch is analyzed by the combination of a TDS and an energy spectrometer.

### Synchronization system

For pump-probe experiments to benefit from femtosecond XUV pulses delivered by FELs, synchronization of laser systems and the electron bunch timing on the same time scale is essential. The synchronization system at FLASH is implemented with length-stabilized optical fibers distributing trains of laser pulses with a repetition rate of 216.667 MHz [7]. These trains of optical pulses can be directly applied in electron beam diagnostics like bunch arrival monitors (BAMs) [8] or used for the synchronization of optical lasers using balanced optical cross-correlators (OXC).

## MEASUREMENT OF THE BEAM-BEAM JITTER

### Establishing laser-electron overlap

For the measurements, we used mildly compressed electron bunches with a peak current of 0.3 kA and an rms bunch duration of about 0.3 ps at an energy of 700 MeV. The electron bunches and the laser pulses from the seeding laser are brought into spatial and temporal overlap in the modulator. To establish the spatial overlap, OTR screen stations close to the entrance and the exit of the modulator are used to image the spatial profiles of both the electron beam and the seed laser beam.

To establish the temporal overlap, the spontaneous undulator radiation emitted by the electron bunches as well as the seed laser pulses are extracted from the electron beamline. The light is sent to a fast photomultiplier tube to reduce the temporal offset of both signals to a few hundred picoseconds. Next, the longitudinal phase space of the uncompressed electron bunch is measured by the above described TDS and the laser timing is scanned electronically in sub-picosecond steps. The laser-induced modulation can then be directly observed on the TDS once the overlap is established. The camera images of the observation screen in the dispersive section were acquired using the FLASH data acquisition (DAQ) system. For this measurement, the variable-gap undulators were open and chicane  $C_1$  after the modulator was set to  $R_{56} = 295 \mu\text{m}$ .

For time calibration of the longitudinal phase space measurement, we determined the centroid position of the

streaked electron bunch for a set of phases of the 2856 MHz RF driving the TDS. From this data, the time calibration was found to be  $(-4.58 \pm 0.21)$  fs/pixel.

### Data analysis

The acquired images are analyzed using standard image processing techniques: After subtracting of a background image, which has been recorded without electron beam, a region of interest (ROI) is determined. As the contour of the longitudinal phase space cannot be predicted, the ROI is determined by an image analysis algorithm. As the actual image of the streaked electron bunch defines the ROI for further analysis, the impact of fluctuations of the RF driving the TDS is greatly reduced.

A series of 200 images was used for this analysis. During the acquisition process seven images have been lost, therefore this image series corresponds to 207 consecutive electron bunches at the full 10 Hz repetition rate of the machine. From the part of the image selected by the ROI, the slice energy spread is determined. The local maximum of the slice energy spread marks the center of the laser-electron interaction. Figure 2 shows the arrival time information extracted from the analyzed TDS images; the corresponding histogram is in the right panel of this figure. From this data set, the relative beam-beam jitter is determined to be  $(57.8 \pm 5.0)$  fs. For the error analysis, the effects introduced by the image analysis procedure, the uncertainty determining the slice with maximum slice energy spread, and the uncertainty of the time calibration of the TDS have been taken into account.

### Discussion

The contributions to the total beam-beam jitter that can be measured independently are (i) jitter contribution of laser amplifier in the seeding laser system, (ii) electron beam jitter measured on the bunch arrival monitor (BAM), (iii) jitter of the optical synchronization system (however, negligible with  $\sim 1$  fs rms [9]), and (iv) contributions of the synchronization of the laser oscillator.

Using the bunch arrival monitor (BAM) downstream of the second bunch compressor chicane of the FLASH linac, the arrival time jitter of the electron bunches has been measured. In the time interval under consideration, the rms

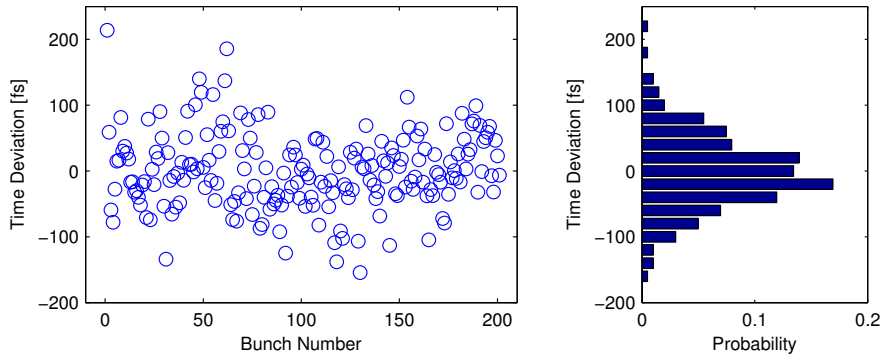


Figure 2: Timing of the laser signatures for a series of 200 images of the longitudinal phase space. In the right panel, the corresponding histogram is shown.

	<b>rms timing jitter [fs]</b>
beam-beam jitter (on TDS)	$57.8 \pm 5.0$
(i) beam arrival time (on BAM)	$31 \pm 13$
(ii) laser amplifier	$10 \pm 1$
(iii) synchronization system	$\sim 1$

Table 1: Compilation of the independently measured rms jitter values. After subtraction of the contributions (i) – (iii), we obtain  $(48 \pm 10)$  fs. In this beamtime, the typical jitter of the laser oscillator of the seeding laser system was 55 fs, which is somewhat overestimated due to the noise floor in the phase noise measurement.

arrival time jitter was 31 fs with the typical uncertainty for the electron bunch parameters being 13 fs. This measurement was performed in single-bunch operation after the upgrade of the FLASH low-level RF (LLRF) control system to a MicroTCA.4-based solution [10]. The typical jitter introduced by the amplifier of the seeding laser system is  $(10 \pm 1)$  fs.

Subtracting contributions (i) – (iii) from the total beam-beam jitter extracted from the TDS images, we obtain  $(48 \pm 10)$  fs. This value includes the jitter of the oscillator of the seeding laser system, for which the typical in-loop measured value in this beamtime was 55 fs. We note that due to the noise floor in the phase noise measurement, which originates from the photodetector, the result of this in-loop measurement of the timing jitter is somewhat overestimated. The measured timing jitter values are compiled in Table 1.

Assuming a desired minimum hit rate of  $p = 0.9$ , a beam-beam jitter of 60 fs rms would require the homogeneous region in the electron bunch to be at least 198 fs long. Practical minimum durations would be longer as we did not consider the finite duration of the seed pulse or budget for small temporal drifts.

### *Measurements at other facilities*

A similar measurement of the relative beam-beam jitter was performed at the seeded FEL user facility

FERMI@Elettra [11, 12]. There, a linearly chirped electron bunch is used to extract the jitter from electron energy spectra measured at the beam dump. The laser-electron interaction in the modulator changes the energy of the electrons in the modulated region, corresponding to a relocation of charge density in the energy distribution. Measured energy distributions are compared with those of a reference bunch, determining the energy of the electrons before modulation. In a linearly chirped electron bunch, the beam energy at which this current reduction is observed can be related to a longitudinal position. Time calibration was found to be  $(0.22 \pm 0.02)$  pixel/fs by deliberately changing the laser timing by  $\pm 100$  fs about the working point. At FERMI, the analysis of 200 consecutive modulated electron bunches resulted in an rms timing jitter of 68 fs [11].

## SUMMARY AND OUTLOOK

In this paper, we show measured values for the relative beam-beam jitter in the FLASH1 seeding experiment that have been obtained from an analysis of the laser-electron interaction that will also be used in seeding experiments. Currently, the jitter is dominated by the RF-synchronization of the laser oscillator of the seeding laser system. An all-optical synchronization of this laser oscillator with a sub-10 fs (rms) timing jitter to the optical reference has already been tested. An upgrade of the laser synchronization to this solution based on a balanced optical cross-correlator (OXC) is expected for this year.

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