GENERATION OF ULTRA-SHORT ELECTRON BUNCHES AND FEL PULSES AND CHARACTERIZATION OF THEIR LONGITUDINAL PROPERTIES AT FLASH2

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Abstract

The free-electron laser in Hamburg (FLASH) is a user facility, delivering soft X-ray radiation, consisting of two beam lines, FLASH1 and FLASH2. The injector and the main linac are shared between both beam lines. Starting in 2014, FLASH2 has been commissioned for user operation.

Currently, there is no hardware installed for the direct measurement of the electron bunch length nor the photon pulse duration at FLASH2. Exact knowledge of the pulse duration is essential for time-resolved user experiments performed at FLASH. Therefore, we are designing a modified beam line, containing a new type of X-band deflecting cavity [1] and a dipole, downstream of the FLASH2 undulator, to map the longitudinal phase space onto a beam screen.

Anticipating the feasibility of measuring the longitudinal phase space with high resolution, a study on optimizing the free-electron laser (FEL) performance for shortest bunches is ongoing.

INTRODUCTION

In order to study processes with femtosecond resolution, there is an increasing demand for ultra-short X-ray pulses. This need has been met by commissioning a short pulse laser at FLASH, which creates short electron bunches directly at the cathode [2]. These short bunches are accelerated and compressed in the FLASH main linac. Downstream from the main linac, the electron bunch trains, each comprising up to 800 bunches, can be distributed between the two undulator beam lines, FLASH1 and FLASH2.

No hardware to measure the electron bunch length directly has been installed in the FLASH2 beam line to date. Since knowledge of the bunch length is essential for time-resolved user experiments, a feasibility study of an X-band transverse deflecting structure (TDS) was performed. Results will be presented in the following.

The generation of ultra-short FEL pulses at FLASH1 has been studied in detail [3]. These studies cannot directly be transferred to FLASH2, however, as the layout differs between the two beam lines. In addition, the FLASH2 undulator gaps are movable, thus enabling the application of a taper. Initial results from studies of FLASH2 will be shown in this paper.

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X-BAND TDS AT FLASH2

The results of the feasibility study of an X-band TDS at FLASH2 designed by CERN for several experiments [1] will be presented in the following. Two operation modes using different injector lasers are being considered for FLASH2. The different parameters are shown in Table 1, where Q is the bunch charge, E is the electron beam energy, σ_t is the root mean square (rms) bunch length, and ϵ is the normalized emittance.

Table 1: Parameters for the two Considered Operation Modes for FLASH2

	Standard operation	Low charge
Q /pC	100 – 1000	20 – 100
E /GeV	0.4 – 1.2	0.4 – 1.2
σ_t /fs	50 – 200	<3 – 50
ϵ /(mm mrad)	1 – 3	0.4 – 1

Experimental Set-up

The TDS will be installed downstream from the FLASH2 undulator section. Its vertical streak will be combined with a horizontal deflection by a downstream dipole. This provides the opportunity to observe the longitudinal phase space distribution of the bunch with FEL-on and FEL-off to gain more understanding of longitudinal beam dynamics. Furthermore, by measuring the slice energy spread it is possible to identify the lasing part of the bunch and obtain an estimate of the photon pulse duration in the absence of slippage [4]. The beam will be imaged using an off-axis screen downstream from the TDS and the dipole to allow for parasitic measurements.

The FLASH2 TDS will consist of two 0.8 m long cavities, both powered by the same 6 MW klystron and a pulse compressor. This will lead to a maximum deflecting voltage of approximately 34 MV.

Optics Set-up and Resolution

To obtain the best possible resolution for longitudinal phase space measurements, the accelerator optics were adjusted as follows.

The vertical particle motion downstream from a TDS at s_0 can be described by [5]

$$y(s) = y_0(s) + S(s) \cdot \left(\zeta + \frac{\sin(\Phi_{RF})}{\cos(\Phi_{RF})} \cdot \frac{c}{\omega} \right) \quad (1)$$

with the initial beam position $y_0(s)$, the Shear-parameter

$$S(s) = \sqrt{\beta_y(s_0)\beta_y(s)} \cdot \sin(\Delta\Psi_y) \cdot \frac{eV_0\omega}{pc^2} \cdot \cos(\Phi_{RF}), \quad (2)$$

the internal bunch coordinate ζ, the radio frequency (RF) phase Φ_{RF}, the speed of light c, the frequency of the RF ω, the vertical beta function at the center of the TDS $\beta_y(s_0)$, the vertical beta function at the screen $\beta_y(s)$, the vertical phase advance between the center of the TDS and the screen $\Delta\Psi_y$, the electron charge e, the deflecting voltage V_0, and the momentum of the electrons p.

The attainable rms longitudinal resolution is given by

$$R_z = \frac{\sigma_{y0}}{S(s)} = \frac{\sqrt{\epsilon_y} \cdot pc^2}{\sqrt{\beta_y(s_0)} \cdot \sin(\Delta\Psi_y) \cdot eV_0\omega \cdot \cos(\Phi_{RF})}, \quad (3)$$

with the unstreaked vertical beam size at the screen σ_{y0} and the normalized vertical emittance ϵ_y. To obtain the temporal resolution Eq. (3) can be rewritten as $R_t = \frac{R_z}{c}$, as the electron bunches are moving with a velocity of c. As the aim is to measure the complete longitudinal phase space distribution of the bunch, a high energy resolution is crucial, which is given by

$$R_\delta = \frac{\sigma_{x0}}{\eta_x} = \frac{\sqrt{\beta_x \epsilon_x}}{\eta_x}, \quad (4)$$

where η_x is the horizontal dispersion at the screen and σ_{x0} is the beam size without dispersion.

For optics matching, two quadrupoles upstream the TDS, four quadrupoles between the TDS and the screen, and four quadrupoles downstream from the TDS can be used. During multi bunch operation, in addition to an optimized resolution, the dump constraints, i.e. $\beta_{x,y} > 1000$ m and $\eta_{x,y} = 0$ m at the dump entrance, have to be fulfilled. The achievable resolution using the optics displayed in Fig. 1 is shown in Table 2. These values are well suited for standard operation, where rms electron bunch lengths of >50 fs are expected to be measured, cf. Table 1.

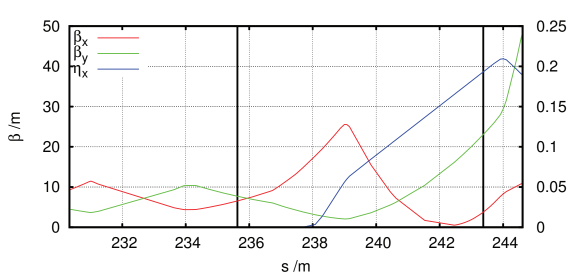

Figure 1: Beta functions and dispersion in both planes plotted against the position s in the accelerator for standard operation. The center of the TDS will be placed at the first black vertical line, the screen at the second one.

For dedicated measurements in low charge operation, a resolution in the order of 1 fs is required. Therefore, measurements can be performed using a special operation mode, where the Twiss functions at the dump are no longer strongly constrained. The accelerator optics for this special operation mode can be found in Fig. 2. Using these optics, a resolution of $\sigma_t = 1.2$ fs and $\sigma_\delta = 1.0 \cdot 10^{-4}$ for short pulse operation can be achieved, cf. Table 2.

Table 2: Achievable Resolution

Mode	Standard operation		Low charge operation	
Optics	Standard	Special	Standard	Special
S	95	83	95	83
R_t /fs	6.2	3.2	2.3	1.2
R_δ /10^{-4}	3.6	2.8	1.3	1.0

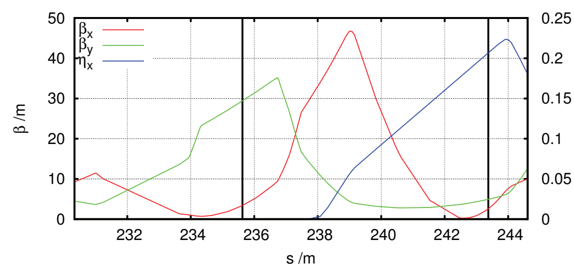

Figure 2: Beta functions and dispersion in both planes plotted against the position s in the accelerator for low charge operation with special high resolution optics, i.e. the dump constraints are no longer fulfilled. The center of the TDS will be placed at the first black vertical line, the screen at the second one.

In the current layout, no kicker is foreseen in the FLASH2 beam line due to space restrictions. To still be able to use the TDS parasitically in combination with an off-axis screen, it is planned to sacrifice a part of the streak to kick the beam vertically. The vertical offset of the beam is calculated using Eq. (1). By operating the TDS at 2° from the zero-crossing, it is possible to kick the beam 13 mm in vertical direction (at full streaking voltage). This leads to S being lower by one per mill, which is negligible in this case. For calibration purposes, where the TDS must be switched off to obtain the unstreaked beam size, it will be possible to move the screen on-axis.

SHORT FEL PULSES AT FLASH2

Using the short-pulse injector laser [2], short electron bunches can be created directly at the cathode. These bunches are then accelerated to energies of up to 1.25 GeV in the FLASH main linac. Additionally, the bunches can be compressed in two bunch compressors to shorten them even further. After acceleration, the bunches are distributed between FLASH1 and FLASH2 using a Lambertson-septum [6]. Initial results from simulations and measurements of short bunches at FLASH2 will be shown in the following.

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Statistical Measurement of FEL Pulse Duration

Short electron bunches, created using the short pulse laser, were sent through the FLASH2 undulator. Two different bunch charges, 70 pC and 38 pC, were used for the experiment. The wavelength was 30 nm and the beam energy 760 MeV. The gain curves were measured using a gas monitor detector (GMD) [7] for SASE pulse energies above 2 µJ. When using only a few undulators, the SASE pulse energy became smaller and the GMD was resolution limited. Therefore, low SASE pulse energies were determined using a micro channel plate (MCP) based radiation detector [8], which was calibrated with GMD values at high pulse energies. An aperture of 10 mm was used for the gain curve measurement to obtain only the central part of the radiation. The measured gain curves are shown in Fig. 3 and are compared with GENESIS [9] simulations. The input bunch length for the simulations was taken from the statistical analysis of the FEL pulse duration, as shown below. The simulated pulse energy is higher in the saturation regime, because the aperture cut some part of the radiation. Furthermore, some properties of the particle beam, like the energy spread, had to be estimated for the simulation, since there is no way of measuring them at FLASH2, yet. Nonetheless, the curves show a similar behavior and the measurements could thus be reproduced.

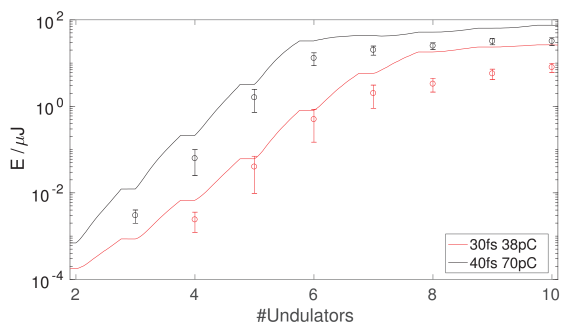

Figure 3: Measured (circles) and simulated (lines) gain curves of short bunches at FLASH2 using different charges. The vertical axis shows the mean pulse energy, the horizontal axis the number of undulators used. The wavelength was 30 nm and the beam energy 760 MeV.

In addition to the gain curves, the fluctuations of the self-amplified stimulated emission (SASE) were measured using the MCP and an aperture of 2 mm. The probability distribution of the radiation energy follows a gamma-distribution [10]

$$p(E) = \frac{M^M}{\Gamma(M)} \left(\frac{E}{\langle E\rangle}\right)^{M-1} \frac{1}{\langle E\rangle} \exp\left(-M\frac{E}{\langle E\rangle}\right), \quad (5)$$

where $M = 1/\sigma_E^2$ is the number of modes in the radiation pulse, $\Gamma(M)$ is the gamma function, and $\sigma_E^2 = \left\langle (E - \langle E\rangle)^2 \right\rangle / \langle E\rangle^2$. The measured fluctuations of the SASE radiation and the corresponding number of modes are plotted along the undulator in Fig. 4. The maximum of fluctuations measured for 70 pC was 0.67 corresponding to 2.9 modes. For 38 pC the maximum of fluctuations was 0.791 corresponding to 1.6 modes. The rms electron bunch length and the full width-half maximum (FWHM) photon pulse duration at the end of the linear regime are given by [11]

$$\tau_{ph}^{min} \simeq \sigma_t \simeq \frac{M\lambda_l}{5\rho} \simeq \frac{M\lambda_l L_{sat}}{5c\lambda_u}, \quad (6)$$

where λ_l is the light wavelength, ρ is the FEL parameter, L_{sat} is the saturation length, and λ_u is the undulator period. For 70 pC the FWHM FEL pulse duration determined from the gain curve measurement at the end of the linear regime is calculated to be 40 fs and 30 fs for 38 pC. From the simulations, we get FWHM pulse durations of the photon pulse of 44 fs for 70 pC and 33 fs for 38 pC. These values are a little bit higher, since for the simulations an idealized model of the bunch and the undulator was assumed, leading to more parts of the bunch contributing to lasing.

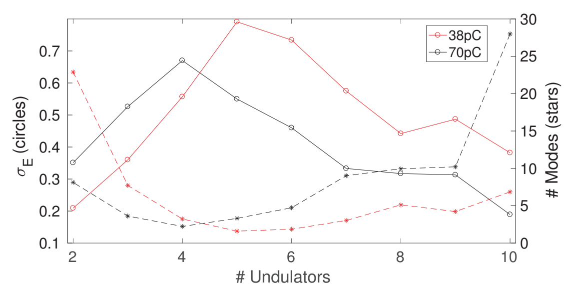

Figure 4: Measured SASE fluctuations (circles, solid) of short bunches at FLASH2 and the corresponding number of modes (stars, dashed) using a 2 mm aperture. The wavelength was 30 nm and the beam energy 760 MeV.

At the current stage, nearly single spike lasing is possible at FLASH2. To achieve single spike lasing, further studies regarding the influence of the FLASH2 extraction arc will be performed. Also, the application of a taper to suppress slippage effects in the saturation regime may be possible.

SUMMARY

A feasibility study for an X-band TDS at FLASH2 was performed. It will be possible to measure the longitudinal phase space distribution of electron bunches with a resolution of up to $\sigma_t = 1.2$ fs and $\sigma_\delta = 1.0 \cdot 10^{-4}$ in a dedicated single bunch mode and $\sigma_t = 6.2$ fs and $\sigma_\delta = 3.6 \cdot 10^{-4}$ in multi bunch mode. To operate the TDS parasitically an off-axis screen will be used and a part of the streak by the TDS will serve to kick the beam onto the screen. It is planned to install the TDS in 2019.

Using the short-pulse injector laser, ultra-short FEL pulses can be created at FLASH2. FWHM FEL pulse durations of 30 fs corresponding to 1.6 modes are possible. Further studies to decrease the FEL pulse duration even further and use the low charge mode routinely, will be performed.

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