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A PolariX TDS FOR THE FLASH2 BEAMLINE

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Abstract

Transverse Deflecting RF-Structures (TDS) are successfully used for longitudinal diagnostic purposes at many Free-Electron Lasers (FEL) (LCLS, FLASH, EU-XFEL, FERMI). Moreover, by installing a TDS downstream of the FEL undulators and placing the measurement screen in a dispersive section, the temporal photon pulse structure can be estimated, as was demonstrated at LCLS and sFLASH. Here we describe the installation of a variable polarization X-band structure (PolariX TDS) downstream of the FLASH2 undulators. The installation of such a TDS enables longitudinal phase space measurements and photon pulse reconstructions, as well as slice emittance measurements in both planes using the same cavity due to the unique variable polarization of the PolariX TDS.[1]

INTRODUCTION

The lasing process in a free-electron laser (FEL) is dominated by the longitudinal parameters of the electron bunches. Hence, the measurement of their longitudinal properties is of utmost importance to control the lasing process. This can, for example, be achieved by means of a Transverse Deflecting Structure (TDS). With this device it is possible to relate the longitudinal coordinate of an electron beam to a transverse one, which then can be imaged using a screen. Additionally, an energy spectrometer, such as a dipole magnet, can be used to relate the beam energy to the other transverse coordinate by deflecting the beam in the plane transverse to the streaking plane of the TDS. By combining both methods, the longitudinal phase space density of the electron bunches can be mapped onto a screen [2]. Additionally, the slice emittance can be measured using a TDS [3, 4]. Such a measurement station is planned as an essential part of the Free-Electron Laser in Hamburg (FLASH) midterm refurbishment and the FLASH2020+ upgrade plans [5]. It will be installed downstream of the FLASH2 undulators to ensure high beam-qualities at FLASH2 as well as brilliant and high-quality photon pulses. The measurement station comprises a novel TDS with a variable polarization feature (PolariX TDS[2]) [6–8] and will be used as an indispensable diagnostic tool for short electron bunches and photon pulses at FLASH2.

In the following, we will describe the optics for longitudinal phase space density measurements and slice emittance measurements in both planes. In addition, tracking simulations for longitudinal phase space measurements as well as photon pulse reconstructions and slice emittance measurements are presented.

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[1] This article contains excerpts from [1].

[2] Polarizable X-band TDS

LAYOUT OF THE TDS DIAGNOSTIC SECTION AT FLASH2

The TDS diagnostic section will be situated directly downstream of the FLASH2 undulators. It will feature two PolariX TDSs [8], which are X-band transverse deflecting structures ($f_{\mathrm{RF}} \approx 12\,\mathrm{GHz}$) with variable polarization yielding arbitrary streaking directions. A technical drawing of the two cavity supports is displayed in Fig. 1. Additionally, a kicker to deflect the beam onto an off-axis screen station will be installed.

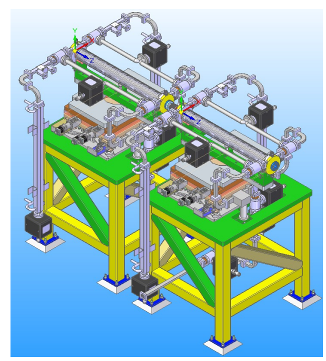

Figure 1: Technical drawing of the supports for the two PolariX TDSs at FLASH2. Courtesy of M. Föse.

The new TDSs at FLASH2 will share their radio frequency (RF) station with the FLASH Forward [9] TDS as both experiments require longitudinal beam diagnostics [7]. The waveguide distribution and RF components can be seen in Fig. 2. The RF source is connected via an RF switch to both experiments. This installation scheme prohibits simultaneous operation, but requires only a single RF station and therefore reduces costs and saves space. The RF source comprises a 6 MW Toshiba E37113A klystron with an Ampegon Type μ, S-Class modulator [8] and is similar to the CERN Xbox3 design [10]. To minimize the attenuation in the waveguides and achieve high deflecting powers, the klystron will be placed as close to the FLASH2 TDSs as possible. Therefore, the klystron will be installed inside the tunnel while the radiation sensitive modulator and low-level RF-rack are placed outside. The klystron and the modulator are connected by pulse cables of 15 m length. The total waveguide length from the klystron to the cavities is about 5 m. In the final stage, an X-band version of the PSI C-band barrel open cavity (BOC) [11] compressor will be installed between the TDSs and the klystron, approximately raising

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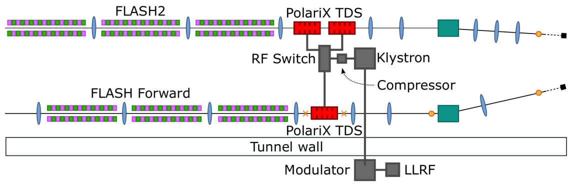


Figure 2: Shared RF system between FLASH2 and FLASH Forward. Courtesy of P. González Caminal.

the input power for the TDSs by a factor of four. The maximum achievable deflecting voltage will then be in the order of 40 MV.

ACCELERATOR OPTICS

The accelerator optics for the longitudinal phase space density measurements can be found in [1]. They are similar to those published in [12]. Temporal resolutions R_t in the order of 1 fs and energy resolutions R_δ in the order of $2 \cdot 10^{-4}$ are expected for low emittance bunches.

Furthermore, the PolariX TDS comprises a variable polarization feature, which allows slice emittance measurements in both transverse planes using the same TDS. This is a unique feature of the PolariX TDS. To fully avail of this feature some design limitations of the beam line have to be considered. As only one screen station is available for the slice emittance measurements, a quadrupole scan has to be performed. Additionally, the screen station should be placed at a point of vanishing M_{16}. Due to space limitations at FLASH2, the screen station can only be placed in the horizontally dispersive section. As a result, the optics have to be matched to achieve $\eta_x = 0$ at the screen

For the optics matching, all quadrupoles between the last FLASH2 SASE undulator and the screen station are used. The emittance reconstruction point is directly upstream of the first quadrupole at s_0. To increase the accuracy of the measurement, seven different optics covering a total phase advance of $\Delta\Psi_{v,\mathrm{total}} = \frac{3}{5}\pi$ in the slice emittance measurement plane v between the screen and the reconstruction point are matched. In the streak direction a high longitudinal resolution is required. In the horizontal plane, temporal resolutions of 3.8 fs to 4.9 fs are achieved for the seven different optics, whereas in the vertical plane all resolutions are in the order of 4 fs.

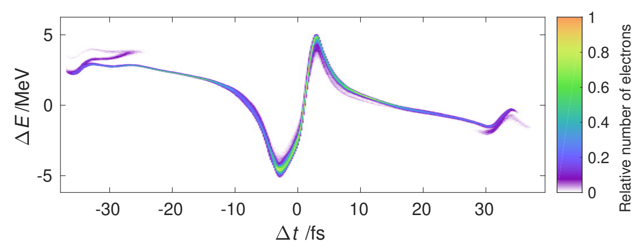
TRACKING SIMULATIONS

Various tracking simulations in elegant [13] were carried out to assess the performance of the PolariX TDSs at FLASH2 regarding the longitudinal phase space density measurement, the photon pulse reconstruction, and the slice emittance measurement in both planes. Examples are presented in the following, a much more detailed analysis is found in [1].

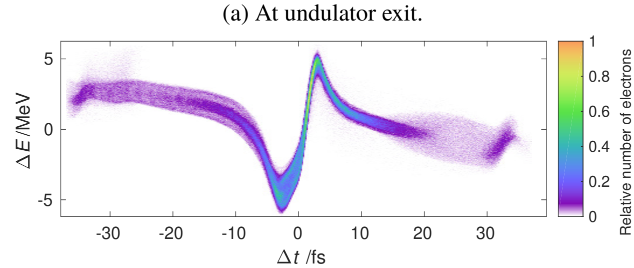
Longitudinal Phase Space Density Measurement

For the longitudinal phase space density measurement, a 20 pC bunch [14] is tracked through the TDS at a deflecting voltage of 34 MV and through the downstream beam line.

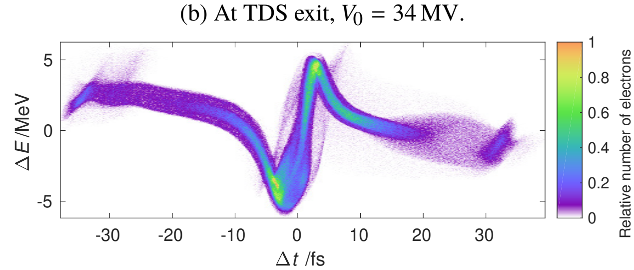
Figure 3 shows the result of tracking simulations for bunches with a charge of 20 pC [14] and a bunch length of 13.8 fs rms. The mean energy is 1 GeV and its longitudinal phase space density at the undulator exit can be seen in Fig. 3(a). As this bunches is very short, the temporal resolution plays a crucial role. At this deflecting voltage of 34 MV the energy measurement is dominated by the induced energy spread. The longitudinal phase space densities at the TDS exit are shown in Fig. 3(b). The induced energy spread at the TDS exit is clearly visible in comparison to the undulator exit. Additionally, even for a resolutions of 0.8 fs differences between the longitudinal phase space density at the TDS exit and the reconstruction at the screen are visible, c.f. Fig. 3(c). In the core part of the bunch, i.e. between −10 fs and 10 fs, the longitudinal resolution limits the resolving capacity of the measurement. The measurement is blurred when compared to the longitudinal phase space density at the TDS exit.



(a) At undulator exit.



(b) At TDS exit, $V_0 = 34$ MV.



(c) Reconstructed. $R_t = 0.8$ fs, $R_\delta = 1.4 \cdot 10^{-4}$.

Figure 3: Longitudinal phase space density reconstruction using a 20 pC bunch [14] as input.

Photon Pulse Reconstruction

The FEL process is simulated using Genesis 1.3 [15]. The particle distribution at the end of the exponential regime is

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then extracted and used to perform the photon pulse reconstruction following [16]. A lasing bunch (lasing-on) and a bunch where the lasing process is suppressed (lasing-off) are tracked through the TDS and onto the beam screen. The screen image is then analyzed and the photon pulse power P in each slice t_i is calculated from the energy loss in each slice [16]

$$P(t_i) = \Delta E(t_i) \cdot \frac{I(t_i)}{e}, \qquad (1)$$

where $\Delta E(t_i) = E_{\mathrm{on}}(t_i) - E_{\mathrm{off}}(t_i)$ is the energy loss, E_{on} and E_{off} are the mean energy for the lasing-on and lasing-off bunch, respectively, and I is the current.

Gaussian bunches with a length of 100 fs and 23 fs at beam energies of 1200 MeV and 700 MeV, respectively, are tracked. The corresponding wavelengths are 6.6 nm and 19.4 nm, respectively.

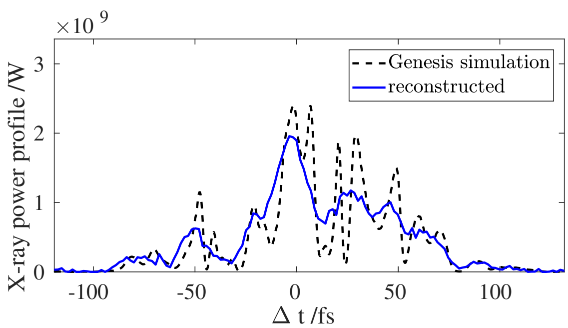


Figure 4: Photon pulse reconstruction of a Gaussian bunch with a bunch length of 100 fs rms at an energy of 1200 MeV using a deflecting voltage of 20 MV. The wavelength is 6.6 nm.

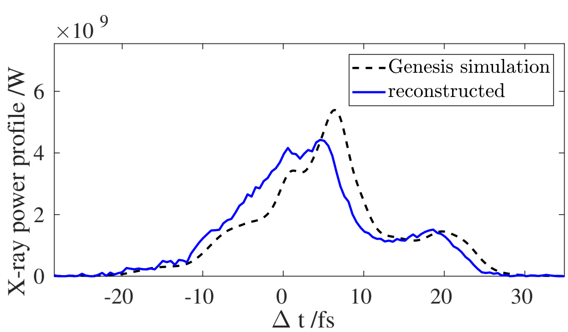


Figure 5: Photon pulse reconstruction of a Gaussian bunch with a bunch length of 23 fs rms at an energy of 700 MeV using a deflecting voltage of 34 MV. The wavelength is 19.4 nm.

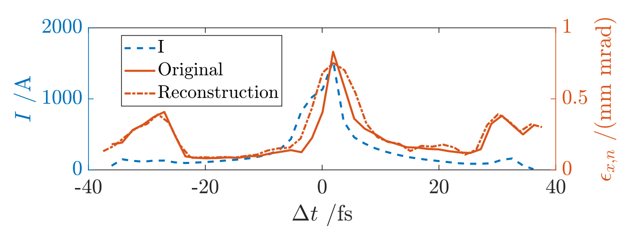
For the reconstruction of the 100 fs rms bunch, c.f. Fig. 4, the influence of the limited temporal resolution is visible, although the effect is rather small. Most of the SASE spikes are still visible in the reconstruction, only the separation of spikes that are very close to one another is blurred.

The reconstruction of the shorter pulse of 23 fs rms, c.f. Fig. 5, closely resembles the actual photon pulse. It shows a large single SASE spike with smaller side peaks.

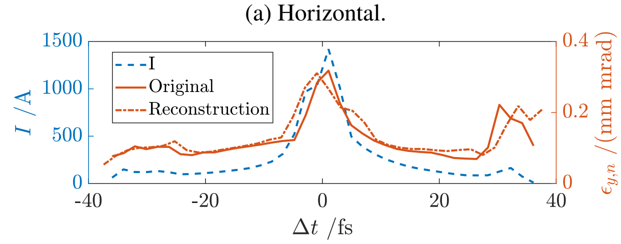
Slice Emittance Measurement

The slice emittance measurement at FLASH2 is performed using a quadrupole scan, the tracking simulations were carried out using elegant [13]. The input distributions are tracked from the emittance reconstruction point directly upstream of the first quadrupole used for the slice emittance measurement to the screen using all of the seven different optics for each transverse plane. The deflecting plane of the TDSs is set to the plane perpendicular to the plane in which the slice emittance is reconstructed. The screen image of each individual measurement is then divided into slices with a fixed width depending of the longitudinal resolution R_t. The central slice is defined as the slice comprising the mean of the distribution at its center [17]. For each individual slice the “rms beam size” is calculated as the square root of the variance of the beam profile [17]. The slices of the tracked bunches are then aligned and for each slice the emittance is calculated according to [18, 19].

The slice emittance reconstruction for a short bunch with a charge of 20 pC is shown in Fig. 6. It reveals, that for the regions of $\Delta t \leq -10$ fs and $\Delta t \geq 10$ fs the reconstructed slice emittances in both planes match very nicely to the original one. Yet, in the region of the current spike, i.e. for -10 fs $< \Delta t <$ 10 fs the influence of the limited resolution of this measurement is visible. Particles from adjacent slices mix in the reconstruction and the reconstructed value for the slice emittance is higher than the original one.



(a) Horizontal.



(b) Vertical.

Figure 6: Vertical slice emittance measurement of a 20 pC bunch [14]. The longitudinal resolution is 2.0 fs, the TDS voltage is 34 MV.

CONCLUSION

This paper and the more detailed work in [1] show, that with the installation of two PolariX TDSs downstream of the FLASH2 undulator section meaningful longitudinal phase space density measurements, photon pulse reconstructions as well as slice emittance measurements in both transverse planes can be performed.

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