FIRST RESULTS OF COMMISSIONING OF THE PITZ TRANSVERSE DEFLECTING STRUCTURE

H. Huck*, G. Asova†, M. Bakr‡, P. Boonpornprasert, A. Donat, J. Good, M. Gross, C. Hernandez-Garcia§, I. Isaev, L. Jachmann, D. Kalantaryan, M. Khojoyan, W. Koehler, G. Kourkafas, M. Krasilnikov, D. Malyutin¶, D. Melkumyan, A. Oppelt, M. Otevrel, M. Pohl, Y. Renier, T. Rublack, J. Schultze, F. Stephan, G. Trowitzsch, G. Vashchenko, R. Wenndorff, Q. Zhao, DESY, Zeuthen, Germany
D. Churanov, L. Kravchuk, V. Paramonov, I. Rybakov, A. Zavadtsev, D. Zavadtsev, INR of the RAS, Moscow, Russia
M. Lalayan, A. Smirnov, N. Sobenin, MEPhI, Moscow, Russia
C. Gerth, M. Hoffmann, M. Hüning, DESY, Hamburg, Germany
O. Lishilin, G. Pathak, Hamburg University, Hamburg, Germany

Abstract

For successful operation of X-ray Free Electron Lasers, one crucial parameter is the ultrashort electron bunch length yielding a high peak current and a short saturation length. In order to effectively compress the bunches during the acceleration process, a detailed understanding of the full longitudinal phase space distribution already in the injector is required. Transverse deflecting RF structures (TDS) can shear the bunch transversely, mapping the longitudinal coordinate to a transverse axis on an observation screen downstream. In addition to the bunch length, the slice emittance along the bunch as well as the full longitudinal phase space can be obtained. At the Photo Injector Test Facility at DESY, Zeuthen site (PITZ), an S-band traveling wave TDS is under commissioning since 2015. This cavity is a prototype for the TDS in the injector part of the European XFEL and has been designed and manufactured by the Institute for Nuclear Research (INR RAS, Moscow, Russia). In this paper, first commissioning results of the system at PITZ are presented and discussed.

INTRODUCTION

Multi-GeV electron beams with high peak currents, required for the operation of X-ray Free Electron Lasers (XFELs), are generated as initially long bunches to reduce space charge effects, and are later compressed at moderate to high energies. Bunch compressors, typically realized as magnetic chicanes following off-crest acceleration, shape the longitudinal phase space for subsequent acceleration and, eventually, for the lasing process in the FEL undulators. To prevent degradation of the overall beam quality, bunch compression in the European XFEL is split into three stages at increasing beam energies. Three transverse deflecting structures are foreseen as diagnostic tools after the second and third bunch compressor and in the injector part of the European XFEL [1, 2]. A prototype of the latter, designed [3] and manufactured by the Institute for Nuclear Research of the Russian Academy of Sciences, is under commissioning at the Photo Injector Test Facility at DESY, Zeuthen site (PITZ).

TDS Working Principle

Quickly changing transverse RF fields deflect electrons depending on their arrival time with respect to the RF phase (Fig. 1). In the linear region around the zero-crossing phase, the longitudinal axis is projected linearly onto the vertical axis of a downstream screen, while the horizontal screen coordinate shows the horizontal beam size of the slices. By scanning the focusing strength of a quadrupole magnet, the slice emittance along the bunch can be obtained. Furthermore, live images of the full longitudinal phase space can be observed when combining the vertical TDS deflection with a horizontally dispersive dipole.

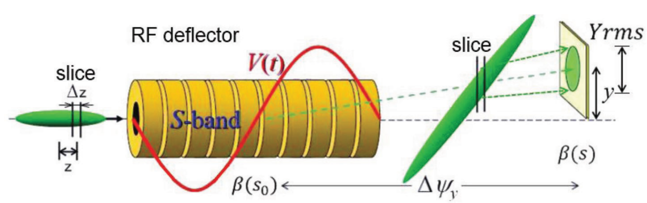

Figure 1: TDS principle: Depending on their longitudinal position, electrons are deflected by transverse RF fields and observed on a screen several meters downstream [4].

Assuming a pure drift space of length L between TDS and screen, a slice of momentum p at the relative longitudinal position z in the bunch hits the screen at vertical position [5]

$$y = S \cdot z = \frac{eV_0 k}{pc} \cdot L \cdot z, \tag{1}$$

where the S-parameter depends on the deflecting voltage V_0 and wave number k. In the general case, the longitudinal

* holger.huck@desy.de
† on leave from INRNE, Sofia, Bulgaria
‡ on leave from Assiut University, Assiut, Egypt
§ on leave from Jlab, Newport News, USA
¶ now at HZB, Berlin, Germany

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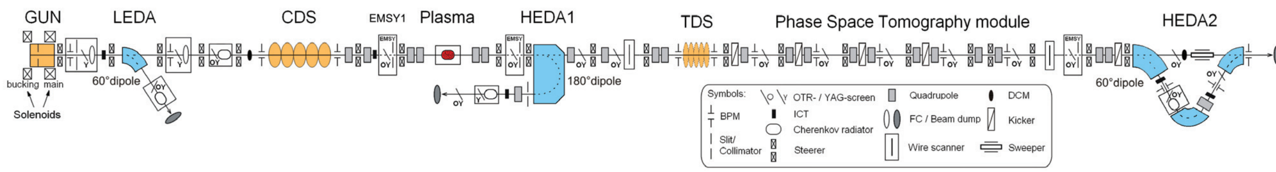

Figure 2: Current layout of the PITZ beamline (PITZ 3.0). Electron bunches which are streaked vertically by the TDS can be monitored on several YAG and OTR screens in the tomography module. Alternatively, their full longitudinal phasespace can be analyzed in the high energy dispersive arm HEDA2, 7.3 m downstream the TDS. During the measurements presented in this paper, the plasma cell was replaced by an empty beam tube.

resolution can be expressed as [4, 5]

$$\sigma_z \gtrsim \frac{2}{eV_0 k} \frac{m_0 c^2}{\sin(\Delta\psi)} \sqrt{\frac{\gamma \epsilon_n}{\beta_{\mathrm{TDS}}}} \qquad (2)$$

with the normalized emittance ϵ_n, beta function β_{TDS} in the TDS, relativistic factor γ and betatron phase advance $\Delta\psi$ between TDS and screen.

Layout at PITZ

The PITZ TDS is installed in the high energy section of the beamline, between the first emittance measurement station EMSY1 and the phase space tomography module (Fig. 2). It is a traveling wave structure similar to the LOLA design [6]. The cell dimensions were selected to have the same cells for all three structures in the European XFEL TDS and are realized in its prototype for PITZ [7]. Table 1 summarizes the most important parameters.

Table 1: Design Parameters of the PITZ TDS

Deflecting voltage	1.7 MV
Input power	2.11 MW
RF Frequency	2997.2 MHz
Pulse length	3 µs
Structure Length	0.533 m
Number of cells	14+2
Phase advance per cell	$2\pi/3$
Quality factor at 20 °C	11780

COMMISSIONING STATUS

A ScandiNova [8] modulator was installed and commissioned at PITZ in early 2015. The on-site acceptance tests were very successful, showing a pulse flatness of 0.24 % within 3.3 µs and a pulse-to-pulse stability of approx. 66 ppm. Both of these values are well inside the ScandiNova specifications (0.3 %, 100 ppm). The modulator is capable of driving a 5-MW klystron, allowing for possible future upgrades of the PITZ RF system.

Following the conditioning of the currently installed 3-MW klystron and the final connection of the waveguide system and RF load to the TDS cavity, the first low-power RF pulses were sent to the structure in early July. Within one shift, the pulses could be synchronized to the electron bunches, and the deflected beam was observed on a YAG screen 1.3 m downstream the TDS.

The structure was conditioned up to intermediate power levels of about 0.5 MW within several days. Currently, the reflected power from the whole waveguide system precludes higher power levels, as reflection must stay below 75 dBm (32 kW) to prevent damage to the klystron. Possible sources of the unusually high reflection are under investigation using a diagnostic load.

The resonance temperature of the TDS was determined by observing the phase difference between signals from the two RF probes in the TDS cells adjacent to the RF input and output cells, while slowly changing the temperature of the cooling water. A value of 50.8 °C was found, which is almost within the designed temperature range of 30-50 °C for the frequency control. In agreement with cold tests [9], the reflected power from the structure does not change measurably within 10 K around resonance conditions.

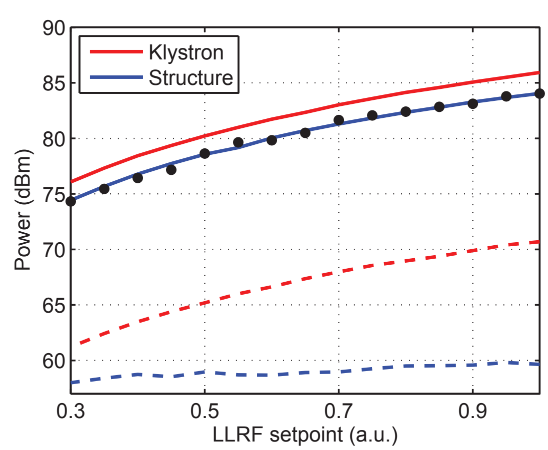

Figure 3: Forward (full lines) and reflected (dashed lines) power readings from the directional couplers at the klystron and deflecting structure. The black dots are estimations of the power in the structure based on the measured electron beam deflection.

Present RF power readings for intermediate power levels from the directional couplers at the klystron exit and at the structure entrance are shown in Fig. 3. The black dots are estimations of the power in the structure based on the actual deflection of the electron beam. For that, the S-parameter

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was determined as described below with a pure drift space between TDS and screen, and then used to calculate the deflection voltage (Eq. 1), from which the power was estimated using simulation results and small corrections [9] accounting for increased attenuation at operating conditions. While these estimations fit very well to the coupler readings, the ratio between forward power at the klystron and structure is unexpectedly large, indicating either losses of more than 30 % in the whole waveguide system, or a wrong calibration of the klystron coupler, which was based on the nominal maximal klystron output.

FIRST MEASUREMENTS WITH ELECTRON BEAM

All measurements were done at machine conditions compliant to the emittance measurements [10] and stability tests for the commissioning phase of the European XFEL. The gun was operated with 640-μs RF pulses at 5 MW and maximum mean momentum gain phase. The booster was set to 3 MW, yielding a mean beam momentum of 21.5 MeV/c in the TDS. After roughly focusing the beam to the first emittance measurement station (see EMSY1 in Fig. 2) with just the main gun solenoid, the beam was further focused onto the observation screens with additional quadrupole magnets right before the TDS. Photocathode laser pulses with a Gaussian temporal profile of 11 to 12 ps length (FWHM) were used [11, 12]. These were generated by introducing a Lyot filter [13] into the regenerative amplifier, thus limiting the bandwidth of the usually 2 ps short laser pulses.

Calibration Procedure

Whenever the power in the structure, the energy or focusing of the beam or the observation screen changes, a new calibration is necessary in order to determine the new S-parameter (Eq. 1). For that, the screen position of the beam centroid was recorded under variation of the RF phase in the TDS. A linear fit of this phase scan yields the zero-crossing phase and the S-parameter.

Proper background subtraction and averaging can have a significant impact on the reliability and reproducability of all TDS measurements, and can be a major challenge for an automated analysis. Different background subtraction methods are under investigation. The best results so far have been achieved with the operator manually defining a region of interest for the calibration code.

Temporal Profiles

A set of preliminary bunch length measurements for different bunch charges (Fig. 4) have been taken. Because the actual beam profiles show significant deviations from a Gaussian shape even at low charges of 100 pC, the real full-width-half-maximum value was determined in both measurement and simulation results, instead of using the statistical rms values. Examples of longitudinal profiles, measured at the first YAG screen after the TDS, are shown in Fig. 5, accompanied by ASTRA simulations assuming a perfect transverse laser profile. While the overall profile shape looks quite similar in experiment and simulation, measured bunch lengths are clearly shorter throughout all measurements. Furthermore, a slight dip near the bunch center is visible in all measurements. Simulations show similar features only at much higher bunch charges around 1 nC.

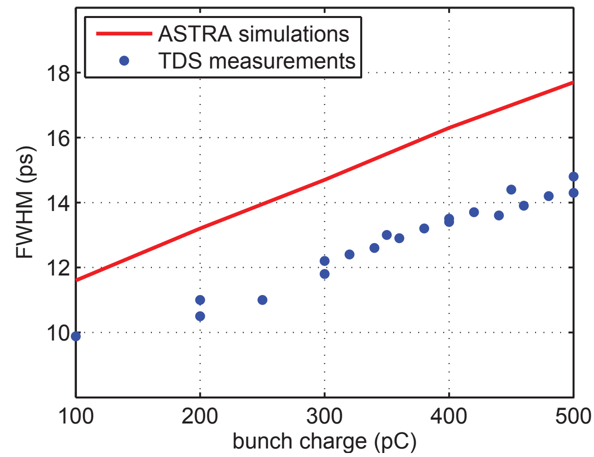

Figure 4: FWHM bunch lengths, measured and simulated, for bunch charges between 100 and 500 pC. The booster phase was tuned for maximum mean momentum gain.

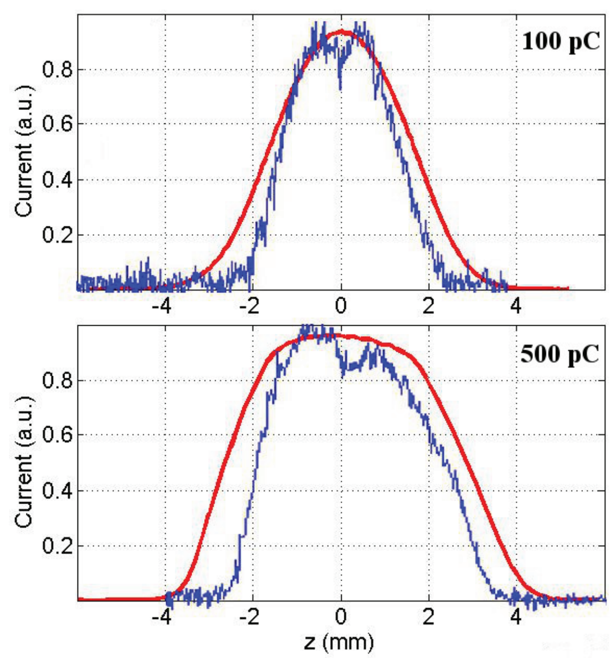

Figure 5: Longitudinal profiles of 100 pC (top) and 500 pC (bottom) bunches after the TDS. The smooth red curves are ASTRA simulations assuming a 11.5 ps (FWHM) long Gaussian photocathode laser pulse, the blue curves are TDS measurements.

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For the lowest investigated charge (100 pC), most dicrepancies could be explained by more realistic simulations using the measured transverse laser distribution as input („core plus halo" model, see [10] and references therein). Results of these simulations are shown in Fig. 6, where the bunch length is plotted versus the RF phase of the booster. The second set of data (green squares) was obtained one month after the first one (blue dots), which was used for the simulations. In that month, the quantum efficiency of the cathode degraded and the actual transverse laser profile presumably changed as well, resulting in different space charge forces during emission. Furthermore, the bunch length can be systematically underestimated in measurements by neglecting low-intensity parts of the beam or by subtracting too much noise or background.

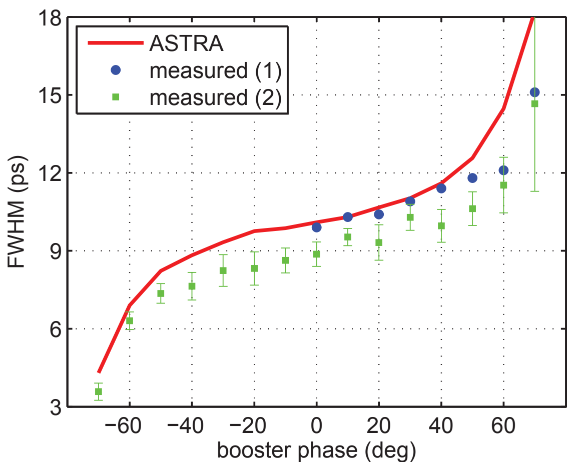

Figure 6: FWHM bunch length versus booster phase for a bunch charge of 100 pC, measured with the TDS (two data sets) and simulated (red line) using the measured transverse laser profile from the first data set (blue dots) as input.

Both the statistical shot-to-shot error of the bunch length measurements and the linearity error of the calibration curve were approx. 4 % for the measurements presented here. The resolution, given by the FWHM spot size of the unstreaked beam, varied between 0.5 and 1.0 ps. Once the nominal deflecting voltage is obtained and beam transport and focusing is optimized, a temporal resolution of ≈ 0.1 ps is expected for pure profile measurements, and 0.2 to 0.3 ps for slice emittance as well as for full longitudinal phase space measurements [4].

Full Longitudinal Phase Space

Sample images of the full longitudinal phase space in the HEDA2 section (Fig. 2) are presented in Fig. 7. These pictures were taken with a very low deflection voltage in the TDS and without optimized focusing between TDS and screen, therefore only exhibiting basic features with a low temporal and momentum resolution. For the center image, the electron bunch was accelerated on-crest in the booster, but on the rising slope of the RF for the left image. Consequently, the head of the bunch shows a higher momentum than the tail in the left image.

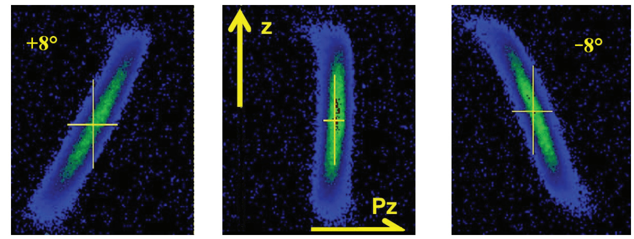

Figure 7: First low-resolution images of the full longitudinal phase space, viewed on a YAG screen after the first HEDA2 dipole magnet. The left and right pictures were taken at +8 and -8 degree booster phase with respect to the maximum mean momentum gain phase, respectively.

CONCLUSION

The PITZ TDS, a prototype for the injector TDS of the European XFEL, is under commissioning since July 2015. Currently, the deflecting voltage is limited to about 50 % of the nominal voltage by the reflected power measured at the klystron, which is under investigation. Power estimations based on the measured electron beam deflection are in good agreement with the reading from the directional coupler at the TDS. First preliminary bunch length measurements suggested a slight overestimation of the bunch length in simulations, which could be partly resolved by more detailed simulations. More detailed measurements and simulations using more realistic transverse laser profiles are foreseen for the upcoming weeks. In the near future, the TDS will also be employed for slice emittance measurements as well as for analyzing the self-modulation of electron bunches inside a plasma cell.

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