PROGRESS ON THE PITZ TDS

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Abstract

A transverse deflecting system (TDS) is under commissioning at the Photo Injector Test Facility at DESY, Zeuthen site (PITZ). The structure was designed and manufactured by the Institute for Nuclear Research (INR RAS, Moscow, Russia) as prototype for the TDS in the injector part of the European XFEL. Last year the deflection voltage was limited for safety reasons, but after thorough investigations of the waveguide system we are now able to operate the cavity close to design specifications. The PITZ TDS streaks the electron beam vertically, allowing measurements of the longitudinal bunch profile, and, in combination with a subsequent horizontal bending magnet, also of the longitudinal phase space and slice energy spread. Furthermore, several quadrupole magnets and screen stations can be employed for horizontal slice emittance measurements using the TDS. This paper describes the progress in commissioning of the hardware, measurement techniques and simulations, and outlines the prospects of reliable slice emittance measurements at 20 MeV/c, where space charge forces complicate the determination of transfer matrices.

INTRODUCTION

X-ray Free Electron Lasers (XFELs) pose stringent requirements on the quality of their driving electron beams, especially in terms of peak current and emittance. Higher peak currents and lower emittances yield higher radiation power and reduce the total undulator length necessary to reach FEL saturation. In particular, the small normalized transverse core slice emittance (i.e. the emittance or "focusability" of the central, high-current parts of the electron bunches), is a major figure of merit. Measurements of the longitudinal charge profile to determine the peak current as well as slice emittance measurements can be performed using a transverse deflecting RF cavity or multi-cell structure (TDS).

Transverse fields inside the structure deflect electrons depending on their arrival time with respect to the RF phase. Near the zero-crossing phase the beam is sheared, linearly mapping the longitudinal charge profile to a transverse, e.g. vertical axis on an observation screen downstream. The horizontal axis can then be utilized for other longitudinally resolved measurements: In combination with a horizontally dispersive bending magnet, live images of the full longitudinal phase space can be observed on the screen, while the quadrupole-scan emittance measurement technique allows for slice emittance measurements [1, 2].

In the simple case of a pure drift space (length L) between TDS and screen, a longitudinal slice of the bunch (relative position z) hits the screen at vertical position [3]

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

where p denotes the electron momentum, c the speed of light, and the shear parameter S depends on the deflecting voltage V_0 and wave number k. In the general case, the longitudinal resolution can be expressed as [3, 4]

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

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

PITZ LAYOUT

At the Photo Injector Test Facility at DESY, Zeuthen site (PITZ), electron guns for the European XFEL and the Free-electron laser FLASH are being tested and optimized. Projected emittance requirements for the nominal European XFEL run parameters have been met [5], recently for the start-up phase as well [6]. In order to measure and optimize also the slice emittance (and other parameters), a TDS is installed in the high energy section of the PITZ beamline, between the first emittance measurement station and the phase space tomography module (Fig. 1). The TDS, designed [7] and manufactured by the Institute for Nuclear Research of the Russian Academy of Sciences as a prototype of the TDS in the injector section of the European XFEL [8, 9], is under commissioning since 2015 [10]. 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 [11]. Table 1 summarizes the most important parameters of the cavity.

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

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Figure 1: 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 phase space 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.

COMMISSIONING STATUS

Initially, the deflecting structure was only conditioned up to intermediate power levels of about 0.5 MW, limited by high reflected power readings near the klystron [10]. Following a thorough recalibration of cables and directional couplers, it was concluded that no urgent changes to the waveguide system are necessary. Afterwards conditioning the structure to higher power levels went smoothly, with only minor vacuum activity. Present RF power readings from the directional couplers at the klystron exit and at the structure entrance are shown in Fig. 2 (top). The blue circles in the bottom plot are estimations of the power in the structure based on the actual deflection of a 23-MeV electron beam. Since this method only works well with a pure drift space between TDS and screen, for higher deflection voltages the streaked beam was clipped by apertures and the screen frame, resulting in strong systematic errors not covered by the error bars.

The maximum obtained power in the structure so far is 1.9 MW, coming close to the nominal design value of 2.1 MW. The limiting factor is still the reflection at the klystron coupler, which has been measured to be almost 80 dBm at 1.9 MW power in the structure. This value is considered safe for the klystron, but stable operation is only guaranteed by the manufacturer up to 74 dBm.

TDS CALIBRATION

The shear parameter S of the TDS is determined experimentally for every bunch length measurement, since not only the power in the structure, but also the beam energy, focusing and even steering of the beam can change its value. The screen position of the beam centroid is recorded under variation of the RF phase in the TDS. A linear fit of this phase scan yields the zero-crossing phase and S. A dedicated Matlab tool handles this calibration procedure and data acquisition simultaneously, as a typical scan with 5-10 images times 5-10 phase steps yields enough statistics for the bunch length, which is calculated for each image separately. In order to properly take into account bunches which are already tilted (i.e. having a transverse-longitudinal correlation) before entering the TDS, the phase scan is repeated on the other slope of the RF (i.e. at inverted voltage). The real bunch length l can then be calculated by a quadratic fit [12], equivalent to $l^2 = (l_+^2 + l_-^2)/2 - l_0^2$, where $l_{+/-}$ denotes the streaked bunch length on both slopes and l_0 the focused, unstreaked beam size (scaled in the same way), which is always measured before the two phase scans.

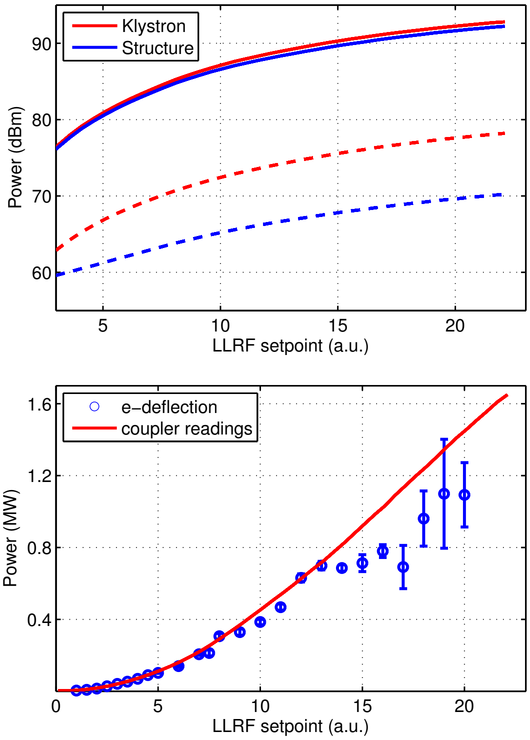

Figure 2: Forward (solid lines) and reflected (dashed lines) power readings from the directional couplers at the klystron and structure (top), and comparison with measured electron beam deflection (bottom).

BUNCH LENGTH MEASUREMENTS

Preliminary TDS measurements [10] suggested a slight overestimation of the bunch length in simulations. To investigate these discrepancies, more detailed measurements for a set of different laser spot sizes and bunch charges have been performed, accompanied by ASTRA [13] simulations. Photocathode laser pulses with a Gaussian temporal profile of 11 to 12 ps length (FWHM) were used, the gun was operated at a gradient of 53 MV/m at the cathode, and the final beam momentum after the booster was 21.5 MeV/c. For the simu-

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lations, the measured transverse laser profiles were taken as input, using a more realistic though still radially symmetric "core plus halo" model [6]. A subset (three different laser spot sizes) is presented in Fig. 3.

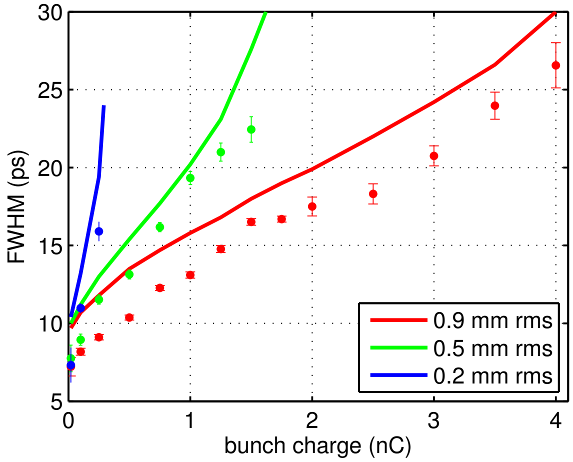

Figure 3: Bunch length (FWHM) vs. bunch charge, measured (dots) and simulated (lines), for different rms laser spot sizes (0.2, 0.5 and 0.9 mm) on the cathode.

The overall, qualitative trend is the same in measurements and simulations. As expected, the bunch length primarily depends on laser intensity, quickly growing with growing space charge density at the cathode. When approaching the space charge limit (i.e. maximum extractable charge), the bunch length reaches values of 20-30 ps. However, the measured bunch length is consistently shorter than the simulated one, by several ps. This discrepancy is neither explainable by statistical errors (error bars) nor by phase jitters. Possible explanations are systematic measurements errors (see below), deficiencies of the emission model, or shorter laser pulses, since their actual length and shape could not be measured last year. While many discrepancies vanish under the assumption of 9-ps pulses (Fig. 4), values close to the space charge limit still do not agree or are even worse as in the case of 0.375 mm spot size.

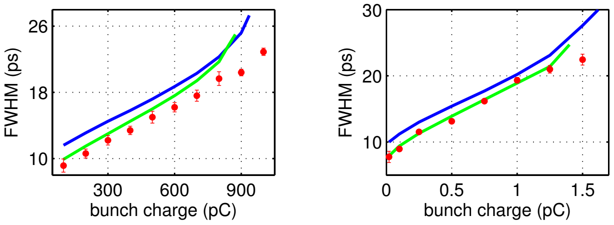

Figure 4: Bunch length (FWHM) vs. bunch charge for rms laser spot sizes of 0.375 mm (left) and 0.5 mm (right). Dots are TDS measurements, blue and green lines ASTRA simulations assuming Gaussian laser pulses of 11.5 and 9 ps, respectively.

During the measurements, strong inhomogeneities (burned spot and vertical gradient) in the sensitivity of the YAG screen were observed, which are believed to be the major systematic error source.

The shot-to-shot standard deviation of the measured bunch lengths as well as the linearity error of the calibration curve were approx. 4 % for the measurements presented here. In future, this error might be reduced by RF feedback, better fitting routines, and more homogenous screens. Furthermore, normalization of the raw images by a screen sensitivity map is under consideration.

The temporal resolution is given by the FWHM spot size of the unstreaked beam. It varied between 0.5 and 1.0 ps, but should go down with higher deflecting voltage and better focusing to ≈ 0.1 ps for pure profile measurements, and 0.3 ps for slice emittance as well as for full longitudinal phase space measurements [4].

SLICE EMITTANCE

Motivation

At PITZ, the projected emittance is usually measured using the slit-scan method, shortly after the CDS booster (Fig. 1) at a beam energy of 20-24 MeV. The main solenoid as only focusing element (beside RF fields) is used to fine-tune the alignment of slices in order to minimize the projected emittance at the measurement station. Recent measurements and simulations have shown that, for the case of long (11 ps FWHM) Gaussian cathode laser pulses, the projected emittance cannot be reduced by increasing the gun gradient from 53 to 60 MV/m, although the slice emittance should go down. Furthermore, projected and slice emittance are not generally minimized by the same solenoid current. This is illustrated in Fig. 5, which shows the evolution of beam size and emittance along the PITZ beamline, simulated in ASTRA for a bunch charge of 100 pC and a laser spot size of 0.2 mm (rms) on the cathode. Here, the projected emittance and core slice emittance are minimum when focusing roughly to the end and the start of the booster, respectively.

Measurement Technique

First tests of scanning the gradient of a single quadrupole right before the TDS and using linear matrix optics to determine the slice emittance showed that this simple approach is not feasible for PITZ. The obtained emittance values were much higher than in simulations, and the statistical errors, obtained by error propagation from the confidence levels of the fit parameters, were of the order of 100 percent. There are several reasons for that. Firstly, space charge forces at low energies of ≈ 20 MeV significantly influence the transverse focusing and thus the transport matrices. Secondly, single-quad scan implies strong changes of the beam size and the intensity on the observation screen, yielding to systematic errors due to limited dynamic range, noise handling and slice mixing, and to strong statistical errors when the horizontal beam size approaches the resolution of the optical system (mostly the pixel size).

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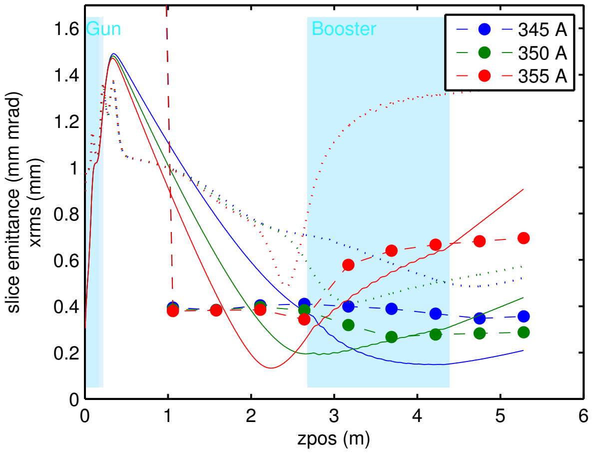

Figure 5: Evolution of the projected emittance (dotted lines), core slice emittance (dashed lines/circles) and beam size (solid lines) along the PITZ beamline. The colors refer to three different solenoid currents.

In order to overcome these issues and obtain reliable slice emittance measurements at PITZ, the following approach will be tested in the upcoming measurement weeks.

In a first step, the projected emittance is experimentally minimized by tuning the solenoid strength. Using the slit-scan technique, not only the projected emittance but also the Twiss parameters are determined, which can be used as input for space charge matching simulations. Thus a set of N quadrupole settings suitable for a multi-quad scan [2] can be obtained. The main idea here is to keep the beam size σ_i on the observation screen roughly constant (but not to small, see above), while scanning the (horizontal) betatron phase. For each longitudinal slice, the emittance is finally derived from the beam moments $\langle x_0^2\rangle$, $\langle x_0'^2\rangle$, $\langle x_0 x_0'\rangle$ at the reference point (i.e. the starting point of the matching simulations), which can be obtained by solving

$$\sigma_i^2 = {R_{11}^i}^2\langle x_0^2\rangle + {R_{12}^i}^2\langle x_0'^2\rangle + 2R_{11}^i R_{12}^i\langle x_0 x_0'\rangle, \tag{3}$$

with the measurement index (i.e. quadrupole setting) $i = 1..N$ and transport matrices R derived from simulations. In a last step, the solenoid strength can be fine-tuned (re-matching required) to minimize the slice emittance.

CONCLUSION AND OUTLOOK

The PITZ TDS, a prototype for the injector TDS of the European XFEL, is now operated near design specifications, and used for measuring the bunch length and longitudinal phase space. There is a strong request in slice emittance measurements using the PITZ TDS, and a measurement procedure that should overcome the difficulties of space charge forces at 20 MeV is under development. In the near future, the TDS will also be employed for analyzing the self-modulation of electron bunches inside a plasma cell, as well as for slice energy spread measurements, which might enhance the understanding of the microbunching instability.

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