SIMULATION OF THE LONGITUDINAL PHASE SPACE MEASUREMENTS WITH THE TRANSVERSE DEFLECTING STRUCTURE AT PITZ

D. Malyutin, M. Krasilnikov, M. Otevrel, F. Stephan,
DESY, 15738 Zeuthen, Germany

Abstract

The main goal of the Photo Injector Test facility at DESY, Zeuthen site, (PITZ) is the development, optimization and detailed characterization of electron sources for short wavelength Free Electron Lasers (FELs) like FLASH and the European XFEL. For a successful operation of such type of FELs the injector must produce high quality electron bunches, short enough in duration with high charge and small transverse emittance value. Installation of the Transverse Deflecting Structure (TDS) at PITZ will provide the possibility for detailed characterization of the bunch temporal profile, bunch transverse slice emittance and longitudinal phase space.

The TDS cavity is currently installed at PITZ beamline, and commissioning of the whole TDS system is expected in the spring-summer 2012.

In the first part of the paper the PITZ2.0 setup is shortly described. The basic principles of the TDS deflector are introduced. The temporal resolution is discussed. Systematic limitations are estimated. Simulations of TDS measurements applied for PITZ bunch parameters are presented.

INTRODUCTION

Photo Injector Test facility at DESY, location Zeuthen (PITZ) was built as a test stand for the electron source for the European XFEL. A normal conducting L-band 1.6 cell gun cavity with Cs_2Te photocathode produces 6.8 MeV electron bunch with about 20 ps bunch length [1]. Then electrons are further accelerated by a booster cavity up to 25 MeV.

The PITZ beamline (see Fig.1) has the following main components: RF photo gun, focusing solenoids, accelerator structure (CDS booster), two dipole magnets (one in the low energy section after the gun, so called Low Energy Dispersive Arm (LEDA) dipole, and second one in the high energy section after the booster, so called High Energy Dispersive Arm (HEDA) dipole), three Emittance Measurement Stations (EMSY), tomography module. Major differences of PITZ 2.0 setup from PITZ 1.8 are the RF deflecting structure and the dispersion section Disp3 (also called HEDA2) after the tomography module.

The transverse phase space characterization is mainly done at PITZ by a slit scan technique. For the longitudinal phase space measurements a streak camera system in the dispersive sections can be used [2].

The recently installed RF deflecting cavity will give much better time resolution and more possibilities for the bunch longitudinal properties studies than the streak camera system.

In this paper basic principles of the deflector cavity measurements are described. Simulations of the measurement procedure are presented. Time resolution is estimated.

All simulations were performed using the ASTRA simulation code [3].

LONGITUDINAL PHASE SPACE MEASUREMENT

Momentum Measurement Resolution

For the bunch momentum measurement the first dipole of Disp3 and the screen Disp3.Scr1 can be used (Fig. 2, dipole field is along the Y axis). The entrance of the dipole Disp3.D1 is 17.2 m downstream from the gun, bending angle α and radius ρ are 60° and 0.6 m respectively. The distance L between the dipole exit and the screen is 0.65 m.

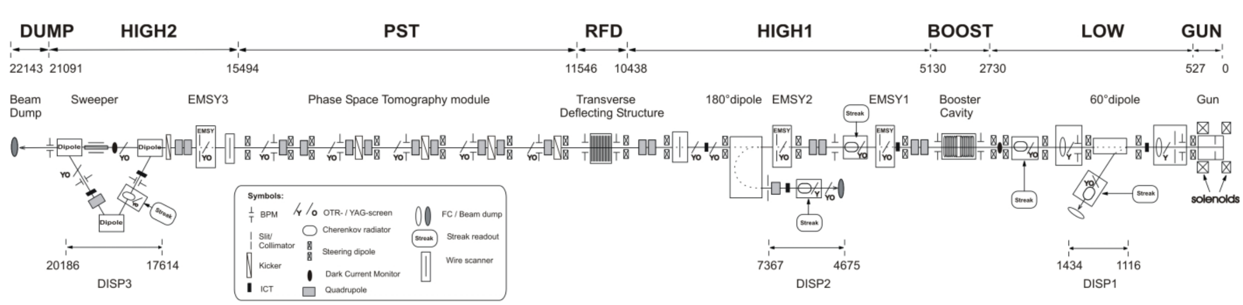

Figure 1: PITZ 2.0 setup.

ISBN 978-3-95450-115-1

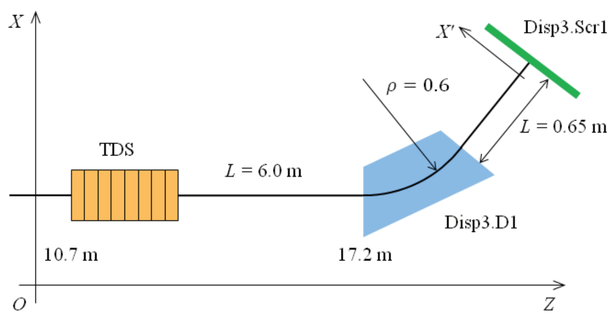

Figure 2: HEDA2 momentum measurement setup. TDS – transverse deflecting structure, Disp3.D1 – dipole magnet, Disp3.Scr1 – observation screen.

The horizontal bunch size at the screen Disp3.D1 is defined by the bunch horizontal phase space and the energy spread [4]:

$$X'^{2}_{rms} = \beta_x \varepsilon_x + (D \cdot \delta p)^2, \quad (1)$$

where X'_{rms} is the rms bunch size at the screen, β_x is the horizontal beta function at the screen position, ε_x is the horizontal bunch geometrical emittance, D is the dispersion at the screen position $D = \rho(1-\cos(\alpha))+L\sin(\alpha)$, L is the distance between dipole exit and screen, ρ and α are dipole bending radius and bending angle, respectively. $\delta p=\Delta p/p$ is the relative RMS momentum spread of the bunch.

The minimum achievable momentum resolution can be defined as such an momentum spread which is needed to have the bunch size due to dispersion and momentum spread equal to the bunch size due to the emittance and beta function. For this case we have the following limitation for the momentum resolution:

$$\delta p \geq \frac{\sqrt{\beta_x \varepsilon_x}}{D}. \quad (2)$$

For example, if $\sqrt{\beta_x \varepsilon_x}$ = 0.3 mm and D = 0.86 m (ρ = 0.6 m and L = 0.65 m) eq. (2) yields $\delta p \geq 3.5 \cdot 10^{-4}$, or in other words for the bunch mean momentum of 23 MeV/c the momentum resolution will be Δp = 8 keV/c.

TDS Basic Principle

The basic idea how the TDS works is illustrated at Fig. 3. The electron bunch is moving from left to right side, going through the deflection structure, is deflected there and then hits a screen.

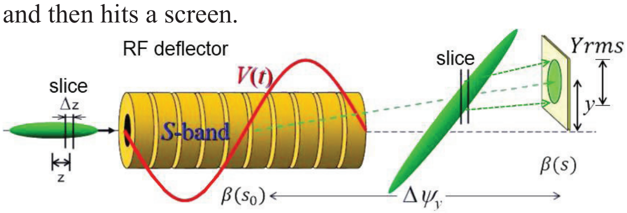

Figure 3: TDS basic: how it works.

The deflection angle which each electron gets during propagation through the structure linearly depends on the electron longitudinal coordinate inside the bunch (here it was assumed that the bunch length is much shorter than the RF wavelength).

To estimate the strength of the deflection let's assume that we have a slice of our bunch with length Δz and longitudinal position inside the bunch z relative to the bunch center. We also assume that electrons, which are in the bunch center, come to the TDS at zero RF phase, i.e. they don't see any deflecting RF field during propagation through the structure. The mean position of our bunch slice at the screen can be obtained from following equation [5]:

$$y = \theta \cdot L = \frac{eV_0 k}{pc} z \cdot L = S \cdot z, \quad (3)$$

where θ – deflection angle, L – distance between TDS and screen, V_0 – deflecting voltage amplitude, k – wave number ($2\pi f_{RF}$/c), p – bunch mean momentum. Here the shear parameter S was introduced as following:

$$S = \frac{eV_0 k}{pc} L. \quad (4)$$

In general case, if we have magnetic elements between the TDS and the screen (e.g. quadrupoles), the shear parameter will be modified as [5]:

$$S = \sqrt{\beta(s)\beta(s_0)} \sin(\Delta\psi_y) \frac{eV_0 k}{pc}, \quad (5)$$

where $\beta(s)$ is the vertical beta function at the screen, $\beta(s_0)$ is the vertical beta function at the TDS, $\Delta\psi_y$ is the phase advance of the vertical beta function between TDS and screen.

TDS Time Resolution

The vertical size of the bunch slice at the screen (see Fig. 3) can be calculated as [5]:

$$Y^{2}_{rms} = \beta_y \varepsilon_y + (S \cdot \Delta z)^2, \quad (6)$$

where ε_y is the vertical emittance at the screen position, Δz is slice length.

Two slices of the bunch can be resolved if the distance between their images on the screen will be bigger than vertical size of the one of them. For this, the minimum resolution length can be estimated for the negligible slice length as follow:

$$\delta z = \frac{\sqrt{\beta_y \varepsilon_y}}{S}. \quad (7)$$

For the geometrical emittance value $\varepsilon = 2.2 \cdot 10^{-8}$ mm·mrad (normalized $\varepsilon_N \sim 1$ mm·mrad), $\beta(s_0) = 1.0$ m, $\beta(s) = 4.1$ m, $\Delta\psi_y = 110$, $p = 23$ MeV/c and $f_{RF} = 3$ GHz and deflecting voltage 0.6 MV TDS longitudinal resolution will be 0.3 ps.

TDS Induced Energy Spread

The working principle of the TDS cavity is based on the Panofsky-Wenzel theorem [6] according which the longitudinal gradient of the transverse force is proportional to the transverse gradient of the longitudinal force:

$$\frac{\partial}{\partial z} F_{\perp} = -\Delta_{\perp} F_{\parallel}. \qquad (8)$$

In result, electrons, which are going through the cavity off axis, will experience longitudinal electric field. The total relative energy spread for the electron bunch can be estimated by the following equation [7]:

$$\sigma_{\delta} = \frac{eV_0 k}{pc} \sigma_y, \qquad (9)$$

where σ_y is the vertical RMS bunch size inside the TDS.

For an RMS bunch size inside the cavity σ_y of 0.4 mm, mean beam momentum of 23 MeV/c, $f_{RF} = 3.0$ GHz and deflecting voltage 0.6 MV the energy spread will be about 15 keV.

Measurement Setup

For the longitudinal phase space measurements the TDS cavity together with the first dipole of the Disp3 section will be used. A simple diagram of the setup for those measurements is illustrated in Fig. 2. The TDS cavity entrance is located 10.7 m downstream from the gun, the cavity length is about 0.6 m, distance between TDS cavity exit and Disp3.D1 entrance is 6 m.

Simulation Results

In Fig. 4 the simulated longitudinal phase space before TDS (left plot) and the reconstructed longitudinal phase space from a simulated measurement (right plot) are shown.

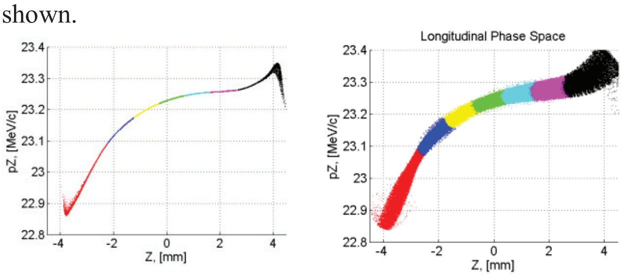

Figure 4: Longitudinal phase space before TDS (left) and reconstructed phase space at the screen after the dipole (right).

The color scheme on Fig. 4 corresponds to seven different longitudinal slices of the bunch with the equal charge, which were chosen in front of the TDS and are shown here just for illustration.

The minimum slice momentum spread presents in the bunch which is coming to the TDS is relatively small – less than 1 keV/c RMS (Fig. 4, left plot). But after the interaction with the RF field of the TDS cavity it grows and became at least 10 keV/c RMS (Fig. 4, right plot). For comparison the RMS momentum spread of the whole bunch is about 90 keV/c in front of the TDS and about 100 keV/c after.

CONCLUSION AND OUTLOOK

Implementation of the TDS cavity into the PITZ beamline together with a new dispersive section will provide the possibility to do longitudinal phase space measurement with momentum resolution better than 10 keV/c and temporal resolution down to 0.3 ps. For a TDS deflecting voltage of 0.6 MV and an RMS bunch size inside the TDS of 0.4 mm, the TDS induced energy spread will be about 15 keV.

Simulations for typical bunch parameters at PITZ were performed, confirming the feasibility of this diagnostic for such type of measurements.

REFERENCES

[1] F. Stephan, et al., "Detailed characterization of electron sources yielding first demonstration of European X-ray Free-Electron Laser beam quality." Phys. Rev. ST Accel. Beams 13, 020704 (2010).
[2] M. Mahgoub, et al., "Longitudinal Phase Space Studies at the PITZ Facility," MOPPP032, these proceedings.
[3] K. Flöttmann, ASTRA, http://www.desy.de/~mpyflo/
[4] H. Wiedmann, Particle accelerator physics, second edition. 1999.
[5] P. Emma, et al., "A Transverse RF deflecting structure for bunch length and phase space diagnostics," LCLS-TN-00-12, The LCLS Technical Notes 2000.
[6] W. K. H. Panofsky, W. A. Wenzel, "Some consideration concerning the transverse deflection of charged particles in radio-frequency field." Rev. Sci. Instrum., 27:967, 1956.
[7] C. Behrens, C Gerth, "On the limitations of longitudinal phase space measurements using a transverse deflecting structure", DIPAC2009, TUPB44.

ISBN 978-3-95450-115-1