SLICE EMITTANCE MEASUREMENT USING AN ENERGY CHIRPED BEAM IN A DISPERSIVE SECTION AT PITZ*

Ye. Ivanisenko†, C. Boulware, L. Staykov, F. Stephan, DESY, 15738 Zeuthen, Germany

Abstract

The photo injector test facility at DESY, Zeuthen site, (PITZ, [1]) develops and characterizes high brightness electron sources for FEL facilities like FLASH and European XFEL. For this purpose a variety of beam diagnostics is being developed and implemented. This article describes an approach for transverse emittance measurements of the electron beam temporal slices at energies of 10-30 MeV. For the method [2], the beam is run off-crest in the booster cavity to produce a linear correlation between each particle's energy and its longitudinal position. Then a 180 deg dipole acts as spectrometer and converts the longitudinal profile into a transverse distribution. In the final step, the beam emittance in the transverse direction orthogonal to the dipole bending plane is measured using a quadrupole scan. The measurement procedure is described in details with the simulation results and conclusion.

INTRODUCTION

High-brightness, low-emittance electron sources are required to achieve SASE FEL operation at short wavelengths. Better understanding of SASE processes require closer attention to the parameters of the radiating part of an electron bunch. In accelerator physics it becomes important to investigate the slice parameters of a bunch, for instance, mean energy and energy spread, transverse size and divergence, peak current, etc. At this point "slice" means longitudinal part shorter than the whole bunch.

PITZ is a photo injector test facility characterizing electron guns for the FLASH facility [3]. PITZ also develops the photo injector for the future XFEL project [4]. A necessary parameter to fulfill lasing at 1 Å at designed brightness is projected transverse emittance of 0.9 mm mrad after the injector section. The electron bunch has 1 nC charge, and the initial laser pulse is 20 ps FWHM. The current laser pulse repetition rate is 1MHz with up to 800 pulses in a train. The train repetition rate is 10 Hz.

As can be seen on Fig. 1, PITZ possesses a variety of electron beam diagnostics. The gun section includes an RF cavity and main and bucking solenoids. After the gun section there is a spectrometer dipole with a YAG screen and an aerogel cherenkov radiator with streak camera read-out optics. This section is called LEDA - low energy dispersive arm.

Next there are several diagnostics screen stations situated along the straight section before the booster. Then the high energy diagnostics begin with the first emittance measurement system (EMSY). It is followed by another screen station with streak readout. Downstream there is a second EMSY station and high energy dispersive arm (HEDA) with an additional diagnostics line on the output. HEDA is discussed in the next section in detail. Further diagnostics as well as steerers, beam position monitors and current transformers are not shown on the figure in order to concentrate on the elements involved in slice emittance measurement.

Two main branches of PITZ diagnostics development are transverse and longitudinal [9] phase space diagnostics. Transverse phase space diagnostics include emittance measurement systems [5], wire scanners,

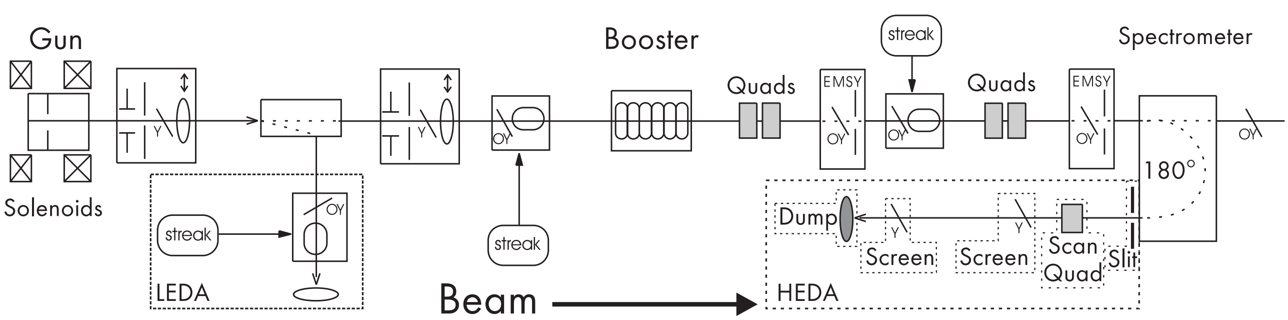

Figure 1: Part of PITZ facility up to the first high energy dispersive section.

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† Contact e-mail: Yevgeniy.Ivanisenko@DESY.de

screen stations (YAG and OTR) and beam optics elements such as quadrupole lenses and steerers. The last winter shutdown [8] included installation of the 180 degree spectrometer that will be used for slice transverse emittance measurements as well as for energy spectrum measurements.

In the future, a transverse phase space tomography module [5] as well as another multipurpose spectrometer will widen facility capabilities.

MEASUREMENT SETUP

After the gun an electron bunch has maximal mean momentum of about 6.6 MeV/c , and a TESLA type normal conducting cavity boosts the bunch momentum up to 14.2 MeV/c. During the next PITZ upgrade an exchange to cut disk structure (CDS) booster cavity [7] is foreseen. It will result in the beam maximal mean momentum of 30 MeV/c. By on-crest acceleration the phase of maximal mean momentum gain is meant. The off-crest phase will mean a phase shift from the maximal mean momentum phase. It can be positive or negative.

The measurement procedure can be split in two phases: a) longitudinal distribution is mapped on a transverse direction (y axis); b) the x plane emittance of the transversely cut bunch part is measured. The first step is realized by accelerating a bunch off-crest in the booster cavity. Particles get a correlation between their temporal position in the bunch and their longitudinal momentum (Fig. 2). The choice of the off-crest phase defines the temporal resolution. This allows the conversion of the beam temporal distribution into a transverse distribution using the 180 deg dipole magnet. The maximum dipole field is 0.46 T, radius - 0.3 m, corresponding 600 mm dispersion.

In the dispersive section the beam passes the quadrupole, 2.5 m drift space and a screen station at the end. The quadrupole scan technique is used for emittance measurements. The quadrupole has an effective length of 0.22 m, aperture of 80 mm, and up to 2 T/m gradient. A YAG:Ce

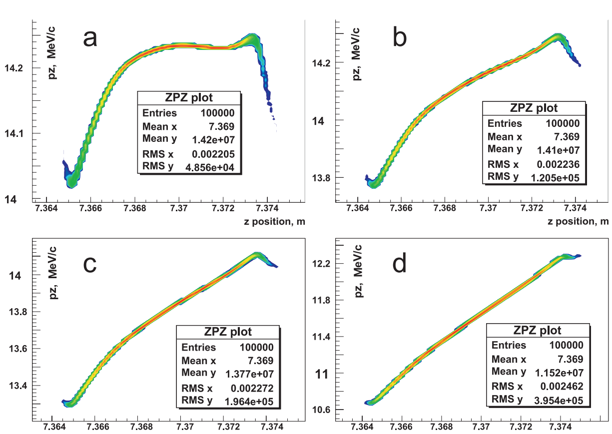

Figure 2: Longitudinal phase space after the booster: a) on-crest; b) +10 deg; c) +30 deg; d) +50 deg.

screen and a CCD camera are used to observe the beam. The measurement technique will allow measurement of transverse emittance in the plane perpendicular to the dispersion.

Currently the slice separation is done at the imaging stage. The camera observes a limited area of the screen. The quadrupole defocuses the bunch along the dispersion axis and focuses along the x axis. At the maximal focusing gradient the bunch shrinks down to 20 μm. A simple numerical experiment shows that for a Gaussian distribution with the rms value two and three times the bin width the discrete rms calculation gives about 1% and 0.1% overestimation correspondingly. The camera has a resolution of 680x512 in the 2x2 binning mode (1360x1024 original) and a square pixel of 9.3 μm width. One to one imaging guarantees the overestimation stays below 1%. On the other hand it limits the sight range along the y axis to 6.3 mm. It is clear that cutting constantly the same part of 6.3 mm for the higher quadrupole gradients corresponds to the shorter slice width. Due to the slice emittance saturation the scan curve is distorted slightly, and each further quadrupole gradient decreases the slice charge. The simulated measurement without the camera noise indicates a fit uncertainty of 20%. The bunch becomes three times larger along the dispersive direction during the scan. In the future there will be a slit installed on the output of the dipole to cut the slices. The 5 mm slit and employment of the 14x7 mm CCD chip (Kodak KAI-2093) will allow the measurement with the whole slice charge in the range of the quadrupole scan. The simulation results in this paper are based on the setup with the slit.

TEMPORAL AND EMITTANCE RESOLUTION

A dipole magnet is used to convert the longitudinal momentum distribution into a transverse distribution along the bending plane axis. By going further off-crest one makes the temporal resolution better and more homogeneous over the slices. Homogeneity is achieved because of stronger linearization of the longitudinal phase space (Fig. 2).

To trace back the temporal part that is analysed after the dipole one has to perform two transformations. The first is done using a linear sweep function of the dipole convoluted with the beam distribution along y axis at the input. The second transformation turns the momentum spread into the temporal slice width using longitudinal phase space of the

Table 1: Mean energy, rms energy spread and resolution of the setup for different phases off crest

$\phi_{offcrest}$, deg	$< E >$, MeV	dE_{rms}, MeV	τ_{res}, ps
+10	14.1	0.121	6
+30	12.5	0.269	2.6
+50	11.5	0.395	1.6
+65	9.8	0.466	0.8

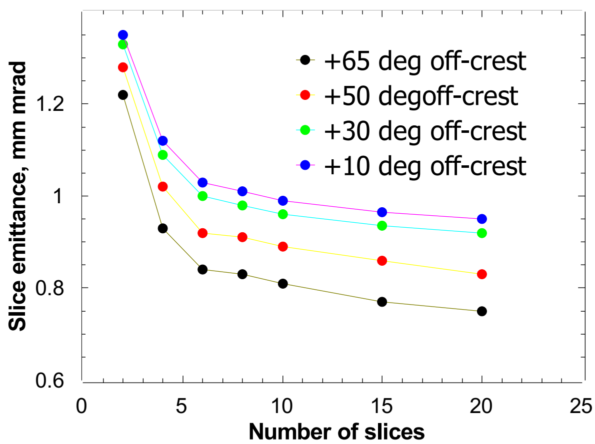

Figure 3: Slice emittance saturation at about 1ps resolution. The slice emittance is smallest at the waist position. The converging beam waist position depends on the off-crest phase

bunch before the dipole.

In Table 1 several phases off-crest are shown together with beam energy, energy spread and temporal resolution. The temporal resolution is calculated as the beamlet energy spread divided over the whole bunch energy spread and multiplied by the electron bunch length before booster. The table values are calculated for the slit of 5 mm width.

Larger off-crest phase improves the temporal resolution, but reduces the signal to noise ratio due to the lower energy of the beam. The chromatism of the bunch in the dispersive section quadrupole limits the emittance resolution. Fig. 3 shows that the average slice emittance of the beam saturates at resolution of 1 ps.

Besides this conversion the dipole acts opposite to a bunch compressor and stretches the beam in the longitudinal direction. The bunch current drops 4 times for the on-crest case and in the off-crest mode the space charge effects are reduced after the spectrometer even more. The dispersion introduces an asymmetry between the bunch transverse profiles.

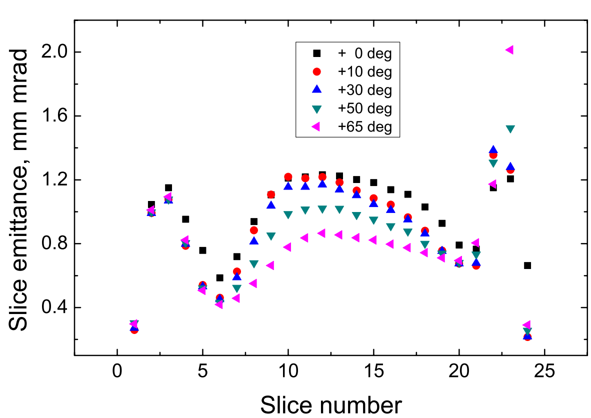

Figure 4: Simulated slice emittance of the beams accelerated with different phases off-crest.

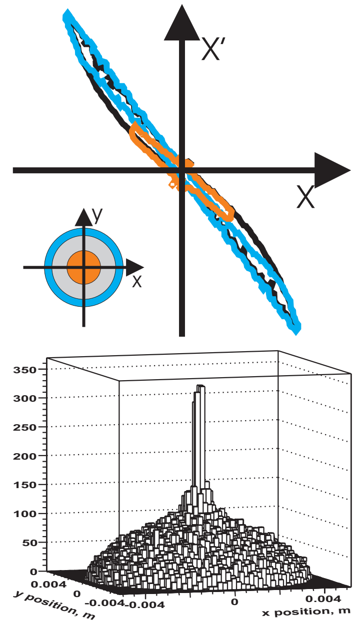

Figure 5: The non linear space charge force separates the phase space ellipses of the central(orange) and the periphery(blue) parts of the transverse profile.

The space charge defocusing force reduces as $1/\gamma^2$ where γ is the bunch energy. This causes different slice ellipses to rotate in phase space on different angle while passing the same distances downstream. The expansion of the beam in the dipole eliminates the space charge influence on the beam and further relative rotation does not occur. Nevertheless beam phase space evolution between the booster and the dipole brings about an individual slice emittance change. The change occurs due to the non-linear space-charge force. If the beam is diverging, the individual slice transverse emittance increases. If it is converging, the individual slice emittance decreases. Near the waist position the slice emittance reaches the minimum value. The waist position differs from slice to slice due to the energy chirp. A simulation was performed using ASTRA code [10]. The results of the simulation are represented on Fig. 4. On-crest acceleration was applied in the gun. The main solenoid current value was chosen to focus the beam on-crest at the last screen in the dispersive arm. Several simulations were done by changing only the offcrest phase. In the simulation, lower mean energy brings the waist closer to the quadrupole input. The solenoid current has to be optimized for each measurement.

The electron bunch is produced by a laser pulse with the uniform transverse distribution. Two and a half meters downstream the electron beam transverse distribution looks as shown in the left bottom corner of the Fig. 5. In order to see the influence of the non-linear space-charge force, the transverse phase space of the central and the periphery parts are shown separately on the top of the full phase space

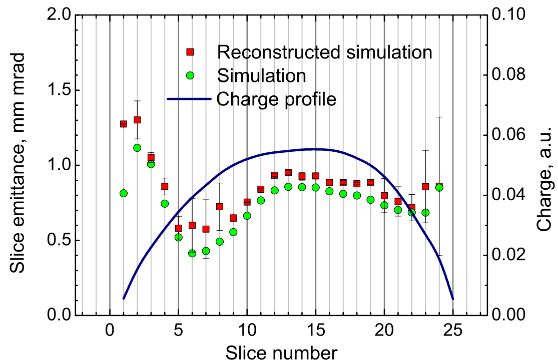

Figure 6: Simulated slice emittance measurement at +65 deg off-crest. Temporal resolution is 0.8 ps

volume of the slice. The parts are indicated on the sketch in the right top corner.

DATA ANALYSIS

The input information for the analysis is an array of image data carrying the information about beam size for the different quadrupole gradients. The data is extracted and the fit is done using a linear optics transport function. The function includes the scan quadrupole and the drift. The original method proposes to fit results with a three parameter function, where parameters include the bunch rms size, divergence, and the correlation term describing the bunch phase space volume before the quadrupole. A possible improvement is to use the screen just after the quadrupole (40 cm distance) to measure the x rms size. An iterative procedure allows the exclusion of the parameter from the fit. This approach reduces the fit uncertainty to a percent level [11].

For example the ASTRA simulation results of the 5 mm slit case are shown on Fig. 6. They correspond to the slice emittance measurement at +65 deg off-crest phase. The simulated values are obtained by direct evaluation of longitudinal slice emittance of a bunch. The reconstructed values are delivered from simulated experiment including dipole tracing, slit cutting, quadruple scan and fitting procedure. Data error represents fit uncertainty and is on average 5%. A systematic offset of ≈10% also exists.

CONLUSIONS AND OUTLINE

The slice emittance measurement method using an energy-chirped beam can be used to characterize the electron source at energies down to ≈ 10 MeV. A major point for low energies is that the slice emittance compensation has to be repeated for each slice . It is done by the solenoid current scan, when the beam position on the slit is adjusted by the dipole.

The signal to noise ratio at high phases off-crest will be improved with the CDS booster cavity installation. Off-crest phases can be used to scan through slices instead of the dipole current. Single slice measurement is done with the same mean energy, but each individual slice represents a completely new longitudinal phase space.

Another source of error can appear when using steerers after the booster. They introduce a correlation between the x and y axes at the observation screen. A steerer kick of 0.5 mrad 5 m before the screen causes the particles separation of 5 mm per 1 MeV/c momentum spread.

The simulation result uncertainty includes 5% of the fit uncertainty and 10% over-estimation. Experimental uncertainties coming from the screen read-out optics, magnetic field flaws, and system parameters jitter have to be determined.

First measurements are planned for this autumn run. In addition to slice emittance measurements using the quadrupole scan, and the single slit scan method will be tested using the EMSY station in front of the dipole input.

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