A TRANSVERSE SLICE EMITTANCE MEASUREMENT SYSTEM USING QUADRUPOLE SCAN TECHNIQUE AND STREAK READOUT AT PITZ*

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Abstract

The Photo Injector Test facility at DESY, Zeuthen site, (PITZ) has been built to develop and optimize electron beam sources that fulfill the requirements of the European XFEL photo injector. The European XFEL requires a transverse emittance of less than 1 mm mrad at the photo injector exit. Although the head and tail of the electron bunch contribute to the projected emittance, it is likely that they have very little influence on the self-amplified spontaneous emission (SASE) process in a FEL. Thus it is important to optimize the emittance of the central slices of the bunch. For this purpose, a setup for transverse slice emittance measurements using a quadrupole scan technique with streak camera readout is being developed at PITZ. In this paper, the measurement procedure is discussed including error estimation and current system limitations. Beam dynamics simulations are presented together with simulations of slice emittance measurements.

INTRODUCTION

The main goal of PITZ is to produce and characterize a high quality electron beam for future operation at the European XFEL. One of the most important electron beam parameters for the generation of high quality FEL radiation is the transverse emittance of the electron bunch. The required normalized slice emittance for XFEL operation is 1.4 mm mrad at the undulator, corresponding to a projected emittance of 0.9 mm mrad at the exit of the injector [1].The projected emittance includes all particles in the bunch; however, not all these particles contribute to the self-amplified spontaneous emission (SASE) process. Thus it is important to possess information on the emittance distribution inside the electron bunch, or in other words, the slice emittance.

A simplified schematic of the current PITZ setup is shown in Fig 1 where the first 10 meters of the PITZ beam line are depicted. The PITZ setup includes a laser driven 1.6 cell L-band RF cavity (the gun) with a Cs_2Te photocathode and a booster cavity. The gun cavity can accelerate electrons up to 6 MeV and the booster cavity provides further acceleration up to 15 MeV (current setup) or 30 MeV (an energy of 30 MeV is anticipated when the new CDS cavity will be installed at the end of this year) [2] [3]. The gun cavity is supplied with a solenoid to compensate for the space charge induced emittance growth. PITZ is equipped with various diagnostics in the low energy section (after the gun) and high energy section (after the booster) including three emittance measurement stations (EMSYs) for projected emittance measurements using a slit scan technique [4].

Thus far, only the projected emittance has been measured at PITZ. For slice emittance measurement, two setups are under development:

1. A system using the quadrupole scan technique together with a streak camera readout.
2. A system using an energy-chirped beam [5].

This paper gives an overview of the first method. The measurement setup is described. Beam dynamics simulations are presented for the current PITZ setup together with expected bunch properties. Finally, systematic limitations of the current setup are simulated and further improvements are proposed.

EXPERIMENTAL SETUP

The current setup for the slice emittance measurements includes a quadrupole (about 5.2 m from the cathode, see Fig. 1) and a screen station with streak readout (6.3 m from the cathode). The method for emittance measurement is based on the quadrupole scan technique using a linear matrix formalism [6]. The beam matrix propagation from the quadrupole entrance to the screen can be described as:

$$\sigma^s = R\sigma^q R^T \tag{1}$$

$$R = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix}, \ \sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix},$$

where σ is the beam matrix (σ^q is the beam matrix at the quadrupole entrance and σ^s is the beam matrix at the screen position) and R is the beam transformation matrix from the quadrupole entrance to the screen position. The measured value is the beam size at the screen position $\sqrt{\sigma_{11}^s}$, therefore the equation may be written with three unknown variables, σ_{11}^q, $\sigma_{12}^q = \sigma_{21}^q$ and σ_{22}^q:

$$\sigma_{11}^s = R_{11}^2\sigma_{11}^q + 2R_{11}R_{12}\sigma_{12}^q + R_{12}^2\sigma_{22}^q \tag{2}$$

Changing the transformation matrix R by altering the quadrupole strength, a system of independent equations may be obtained.

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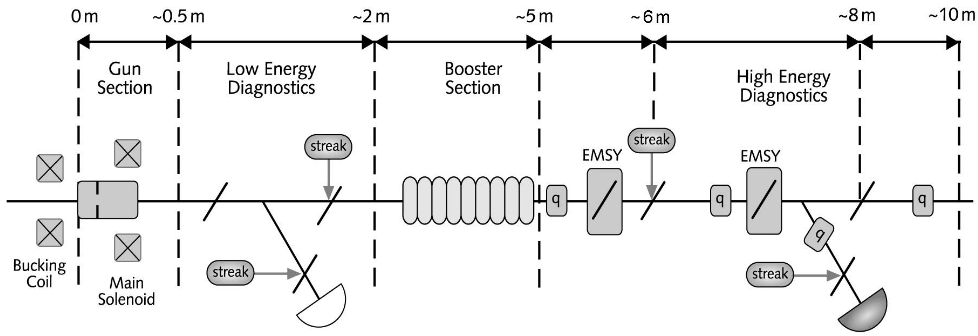

Figure 1: Simplified schematic view of the PITZ setup. The beam propagates from left to right.

Subsequently, the normalized beam emittance can be easily calculated using $\epsilon = \gamma\beta\sqrt{\det(\sigma^q)}$, where γ and β are the energy and velocity factors, respectively.

In this method, the beam size is measured by imaging the transverse electron beam distribution with a screen. In order to measure the slice emittance, one needs a time resolved beam size measurement. A schematic view of the setup for these measurements is shown in Fig. 2.

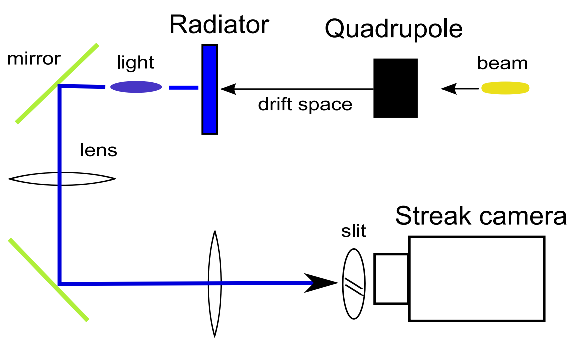

Figure 2: Schematic layout of the slice emittance measurement setup.

Initially, measurements are planned to be carried out with a single quadrupole. The effective length of the quadrupole is 40 mm and the gradient can be varied from -7.5 T/m to 7.5 T/m. The distance to the observation screen (radiator) is about 1.1 m.

A multi-quadrupole scan is also under consideration. For this reason, a double-quadrupole scan experiment is also simulated in this work. The components for the double-quadrupole scan consist of two quadrupoles plus a screen station situated at 5.2 m, 6.8 m and 8.4 m from the cathode, respectively, corresponding to the current PITZ setup geometry. This screen station does not currently include a streak readout, but it is possible to add this in the future.

Currently, a 5 mm thick aerogel radiator is used to produce Cherenkov radiation for longitudinal phase space measurements. Unfortunately, the spatial resolution of this screen is only about 1 mm - far too poor for the slice emittance measurements. For this reason, OTR screens were considered for the slice emittance measurements.

A 30 m long optical line is used to transport light from the radiator to the streak camera [7]. The current optical transport line consists of about 12 lenses. If the broad spectrum of the OTR radiation is used, dispersion in the optical system limits the temporal resolution to 70 ps [8]. Therefore, a 10 nm bandwidth filter is used to measure the longitudinal distribution of the 20 ps beam with about 3 ps temporal resolution. The spatial resolution of the optical system is about 15 line pairs/mm (about 100 μm). Unfortunately, the bandwidth filter significantly decreases the light intensity entering the streak camera. Reflective optics are under consideration for the transmission line in order to reduce dispersion and to achieve the required temporal resolution using broader bandwidth filters thus allowing greater light intensity.

A slit (with a nominal slit width of 100 μm) placed in front of the streak camera is used for the streak measurements. The resolution of the streak camera depends on the slit width and is about 2.5 ps for a 100 μm slit. Reflective optics are used after the slit to image the beam onto the photocathode of the streak camera. After the rotation of the time axes in the streak unit to one of the transverse axes, electrons are converted to photons and imaged on to a CCD camera. The spatial resolution of the streak camera is about 25 line pairs/mm. The total transverse resolution of the setup is required to be of the order of 10% or below. The total temporal resolution of the setup is about 4 ps.

BEAM DYNAMICS

Simulation of the electron beam dynamics is important in order to understand the properties of the bunch which are to be measured. The ASTRA code [9] was used for the beam dynamics simulations. To simulate the propagation of the beam from the cathode to the entrance of the quadrupole, a 2D space charge routine was used.

The typical beam behavior with an optimized laser spot size and solenoid current is shown in Fig. 3. The laser profile used for the simulation was a flat top longitudinal shape with a 20 ps full width at half maximum (FWHM) and a 5 ps rise and fall time, and a flat-top transverse profile with 0.51 mm rms size in both directions. The electron bunch charge was 1 nC and the electron mean momentum was 6.4 MeV/c after the gun and 14.55 MeV/c after the booster. The projected emittance at the location of the measurements was simulated to be 1.17 mm mrad.

Typical slice parameters of the bunch at the entrance of the quadrupole (5.2 m from the cathode) are shown in

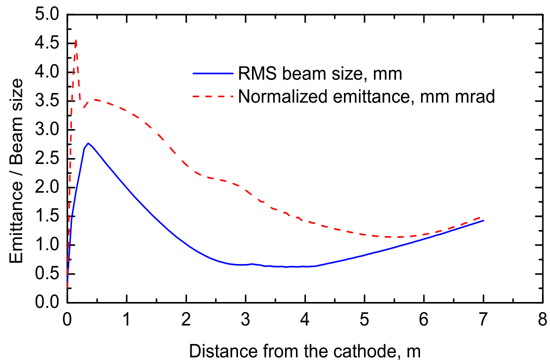

Figure 3: Beam size and beam emittance for the optimized emittance at the quadrupole entrance.

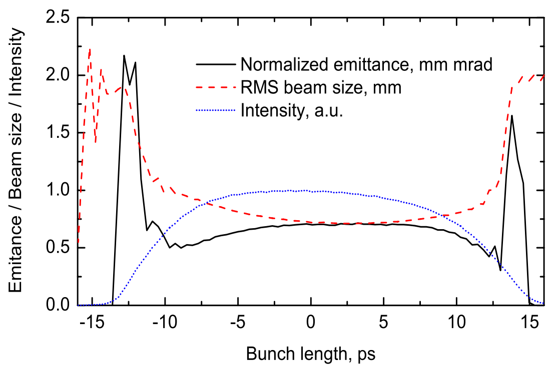

Figure 4: Slice properties of the bunch in front of the quadrupole entrance.

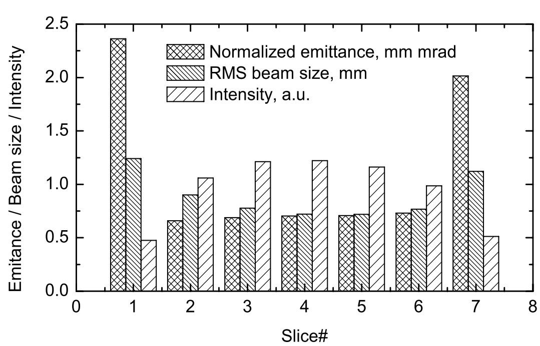

Figure 5: The bunch, divided into 4 ps slices.

Fig. 4. The normalized emittance of the middle slices is less than 1 mm mrad and contains 90% of the bunch charge. However, the head and tail of the bunch have higher emittance and also contribute to the projected emittance. It is likely that only the slices with a small emittance contribute to the SASE process in a FEL. For this reason, it is vital to study the emittance along the bunch.

EXPERIMENT SIMULATIONS

Simulation of the experiment is performed in order to estimate the systematic errors of the setup. The bunch is divided into 4 ps slices, corresponding to the time resolution of the current setup (Fig. 5).

Three main error sources were considered in these simulations:

1. space charge forces, especially at the beam waist;
2. optical resolution;
3. signal cut due to the streak camera slit.

Simulations of quadrupole scan measurements were performed using the ASTRA 3D space charge routine, enabling the dependence of the beam size versus the quadrupole gradient at the screen position to be determined. The fit was performed according to the procedure described above. The discrepancy between the fitted emittance and the simulated emittance at the entrance of the quadrupole is about 10%, on average, for the middle slices.

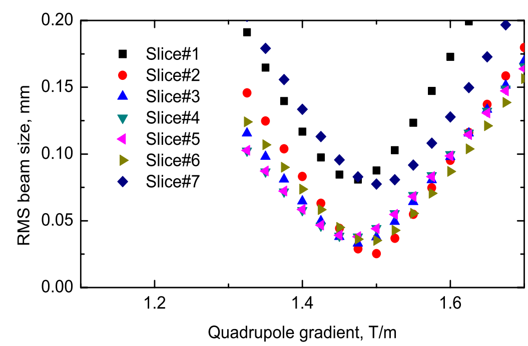

Figure 6: Quadrupole scan measurement simulations. The beam size at the screen position for the single-quadrupole scan.

It is evident that the rms beam size at the waist of the single-quadrupole scan curve decreases to 30 μm (Fig. 6). However, the current resolution of the setup is insufficient to resolve such small sizes. The use of a convolution of the beam distribution (ASTRA output) with a Gaussian point spread function, that corresponds to the resolution of the optical system, results in about 250% (for 100 μm optical resolution) or 90% (for 50 μm optical resolution) systematic increase of the measured emittance.

The transverse plane of the bunch is defined by horizontal X (measurement direction) and vertical Y coordinates. The image size in the Y direction (perpendicular to the measurement direction) can be varied from 1 to 10 mm during the quadrupole scan. For the streak measurements, a 100 μm slit, which cuts about 99% of the signal distribution, should be applied. This cut does not influence the measurements as long as the X profile is independent of the Y position. In reality, however, the beam size in the X direction does depend on the Y direction. Direct calculation of the simulated distribution cut shows that the beam size in the central part of the bunch is higher than the beam size of the whole bunch. Demagnification allows more of the signal to pass through the slit. The typical magnification of the current optical system is 0.5. This effect contributes up to about 30% emittance uncertainty during the measurements in a wide range of magnifications (from 0.1 to 1).

For the central slices, the total uncertainty for 100 μm optical resolution is in the range from 210% to 280%. Even for 50 μm optical resolution, the total uncertainty is about 100%, preventing meaningful measurement of the slice emittance of the central slices.

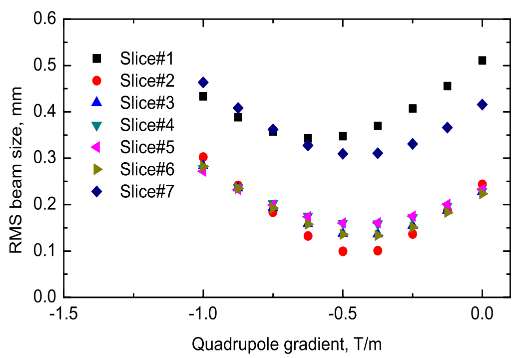

Figure 7: Quadrupole scan measurement simulations. The beam size at the screen position for the double-quadrupole scan.

To improve the resolution of the setup, a double-quadrupole scan is also considered. This avoids the extremely small beam size in the waist of the quadrupole scan curve (Fig. 7) and relaxes the requirements for the resolution of the system. However, a drawback of this improvement is a longer electron beam transport line, and hence greater uncertainty due to space charge forces.

The same procedure used for the single-quadrupole scan yields about 30% (for 100 μm optical resolution) or 10% (for 50 μm optical resolution) systematic increase of the measured emittance. The resultant uncertainty due to the signal cut on the streak camera slit is up to 40%.

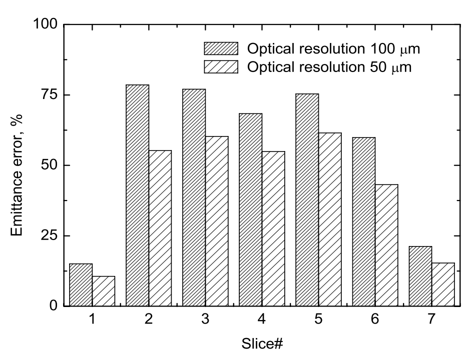

Figure 8: The total systematic error for the double-quadrupole scan.

Fig. 8 summarizes all the systematic error estimation for the double-quadrupole scan measurements. The total uncertainty in the slice emittance measurement is about 75% for the current optical resolution (100 μm) and about 55% for 50 μm optical resolution, preventing measurement of emittance below 1.1 mm mrad.

Several sources of systematic error were not considered: a time jitter which mixes slices and increases the emittance of the outside middle slices; beam position jitter in the direction of the measurement that increases beam size (beam position jitter in the direction perpendicular to the measured one must be less than the slit width); and signal to noise ratio (the noise subtraction procedure usually lowers the measured beam size).

SUMMARY

Electron beam dynamics were simulated for the PITZ setup allowing determination of beam properties to be measured. Slice emittance measurements were simulated. Three types of systematic errors (space charge effect, optical resolution, and signal cut on the streak camera slit) for the slice emittance measurement were considered for the single- and double- quadrupole scans. It is shown that the current setup cannot provide the necessary resolution for the slice emittance measurements. The use of a double-quadrupole scan is considered in order to improve the setup resolution. This shows better reliability but the resolution remains insufficient to obtain desirable uncertainties for measurement of low slice emittance. Further work is required to determine the optimal experimental setup for the slice emittance measurements.

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