SCREEN STUDIES AT PITZ*

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Abstract

The Photo Injector Test facility at DESY in Zeuthen (PITZ) has been built to test and to optimize electron sources that fulfill the requirements of SASE FEL's such as FLASH and XFEL. Basic properties of the electron beam such as momentum, momentum spread, transverse emittance etc. are determined using measurement of the beam size on YAG or OTR screens. Detailed knowledge of the uncertainties and systematic errors associated with these measurements are important to understand the underlying beam physics. The screen stations consist of a screen setup, an optical transmission line to a CCD camera, and the video data acquisition system. In this paper we make a detailed description of the screen based beam size measurement systems that we use at PITZ and discuss the systematic uncertainties associated with each single element of a system.

INTRODUCTION

The goal of PITZ is to provide electron beam capable for SASE FEL operation. Major requirement for such a source is the lowest transverse emittance for bunch charge of 1 nC. The main components of PITZ [1] are a photo cathode UV laser, a Cs_2Te equipped L-band RF gun, space charge compensation solenoids and a booster cavity for conservation of the small beam emittance. Extensive simulation studies have shown that the projected normalized transverse emittance as small as 1 mm.mrad can be achieved with the current PITZ setup, and even smaller values are expected after the foreseen upgrade with a Cut Disk Structure (CDS) type booster cavity [2], improved laser shaping and high gradient in the gun .

The beam emittance is a product of the beam RMS size and divergence when the correlation between them is negligible. In order to compare emittance of beams with different energies normalization with the relativistic factor $\beta\gamma$ is applied. In PITZ the transverse emittance is measured with the Emittance Measurement SYstem (EMSY) [3] which consists of single slit masks for measurement of divergence and YAG or OTR screens for beam and beamlet size measurements. The momentum is measured using a dipole magnet and a YAG screen. Other types of diagnostics at PITZ are Faraday Cups (FC's) and Integrated Current Transformers (ICT's) for charge monitoring and measurement, and longitudinal phase space diagnostics [4].

Such a small emittance pose stringent requirements for the beam diagnostics with accent on the beam size measurement. The aim is a measurement uncertainty below $10\,\%$. The expected range for the RMS beam sizes is from about 2.5 down to 0.2 mm and as small as 50 μm for the beamlets.

METHODS

At PITZ mainly screens are used for measurements of beam size, but in cases of high beam power wire scanners are foreseen in order to avoid radiation or heat damage to the screens. Each screen is combined with an optical transmission line - consisting of mirrors and lenses, and CCD camera and signal transmission line for storage and visualization of the images.

YAG screen

The Yttrium Aluminum Garnet (YAG) scintillator is widely used for the measurements of transverse beamsize, possible drawbacks are saturation[1] at high beam power, multiple scattering of the electrons etc.. At PITZ two different configurations for the YAG screens are used:

- The screen (typically YAG coated Al or Si plates) is placed with $45°$ incidence angle to the beam. A mirror placed outside the beam pipe directs the light to the CCD camera. The main contribution to the uncertainty in this case is the depth of field associated with the screen mounting with respect to the optical plane. Those are typically used in the low energy part of PITZ.
- The screen is mounted with normal incidence angle to the beam. There the scintillation layer of YAG powder is coated on the back side[2] of a Si wafer, a mirror placed next to the screen directs the light out of the vacuum chamber where an additional mirror redirects the light to the CCD camera. Since the electrons must pass through the matter (thickness about 0.275 mm Si and a YAG layer of about 5 - 20 μm), they are subject of multiple scattering which contributes to the measurement uncertainty.

OTR screen

At PITZ the Optical Transition Radiation (OTR) screens are mounted with $45°$ incidence angle, typical characteristics of OTR's are high spatial resolution, narrow angular

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[1] It was shown that at PITZ the saturation contribution is negligible [5]

[2] with respect to the electron beam

distribution of the emitted light that implies high light collection, no saturation effects are expected. Drawback is lower light output with respect to the YAG screen and the depth of field problem associated with the 45° geometry.

Optical system

The optical system includes a system of mirrors and an optical lens. Typical aperture of optical system at PITZ is 0.05 rad with a distance between the center of the screen and the image plane of about 0.5 m. The optical resolution of the system depends on the magnification and is found in the range 20 mm^{-1} $\div$ 50 mm^{-1} for the magnification range 0.1 - 1.

CCD camera

An important element of a screen station is the CCD camera. Main features of a CCD camera are spatial resolution - defined from the total number of pixels over the size of the projected area in mm, and the digital resolution of the CCD chip defined by the Analog to Digital signal Conversion (ADC) associated with the camera. The CCD chip used at PITZ has dimensions 782x582 pixels with pixel size of 8.3 μm and 8-bit analog to digital converter, placed after a long analog line (40 - 60 m). Major upgrade of the transverse beam measurements diagnostics will be the foreseen installation of new 12 bit digital cameras.

MULTIPLE SCATTERING

To simulate the passage of electrons through the material of the screen in normal incidence angle case, the simulation package GEANT4 [6] was used. Gauss function was taken as initial particle distribution and simulations were done for two different initial RMS sizes of the beam σ = 0.1 mm and σ = 0.5 mm, 1e6 particles were used. The deviation $\delta\sigma = \sigma_s - \sigma$ of the image size σ_s from the original electron beam RMS size σ is shown in fig. 1 as a function of the screen (Si) thickness. This difference gives a systematic uncertainty in the order of 5 % for beam size of 0.1 mm and screen thickness of 0.275 mm. It was shown [5] that above 10 MeV the point spread function does not depend on the energy.

OPTICAL RESOLUTION

The response of any real optical system to a point source is a spot with a finite size. The degradation of the beam image due to the finite optical resolution $f_{deg}(x)$ can be estimated from a convolution of the distribution of the point spread function $g(x)$ and the initial distribution $f(x)$.

$$f_{deg}(x) = \int_{-\infty}^{\infty} f(y-x)g(y)dy. \qquad (1)$$

As a response function $g(x)$ we use the Gauss distribution. The description of the optical resolution of optical systems

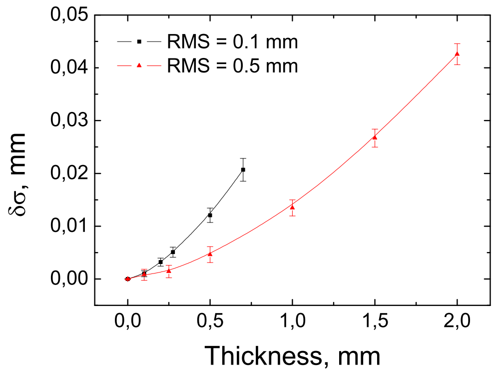

Figure 1: GEANT4 simulations of RMS beam size deviation due to the multiple scattering as a function of the screen thickness. Electron energy is 13 MeV.

is made with the so called Modulation Transfer Function (MTF) formalism.

$$z(\omega) = \int_{-\infty}^{\infty} g(x)e^{-i\omega x}dx, \qquad (2)$$

where ω is called spatial frequency. The optical resolution ω_0 is often defined as a solution of the Eq. (2) when $z(\omega_0) = 0.1$. In fig.2 the difference $\delta\sigma/\sigma = (\sigma_{deg} - \sigma)/\sigma$ between the RMS sizes of the functions $f_{deg}(x)$ and $f(x)$ related to the initial beam size is shown as a function of the initial beam size for two common resolutions used at PITZ.

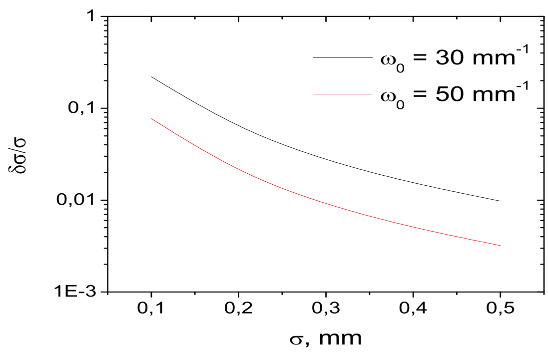

Figure 2: Influence of the optical resolution on the measured beam RMS size.

DEPTH OF FOCUS

The finite thickness of the scintillation layer or the angle (45°) between the screen and the image plane of the optical system are implying different optical paths between different parts of the image on the screen and the image on the CCD chip. This results in an additional uncertainty of the measured beam size. A point source situated at a distance d from the image plane results in a spot with radius:

$$R = d \cdot \tan\alpha \quad (3)$$

here α is the light cone, in case of YAG screen this is the optical aperture of the system (~0.05 rad), for OTR it scales inversely proportional to the relativistic momentum $\alpha = 1/\gamma$. Numerical integration was applied on initial Gauss distribution with 0.1 and 0.5 mm RMS sizes. The results are shown in fig. 3. Because the convergence for $R < 0.2\,mm$ is bad, the result is fitted with 4-th order polynom to estimate the values for smaller R. It is visible, that to keep the uncertainty in the desired range one should restrict $R \leq 0.1\,mm$. In the case of YAG d must be kept

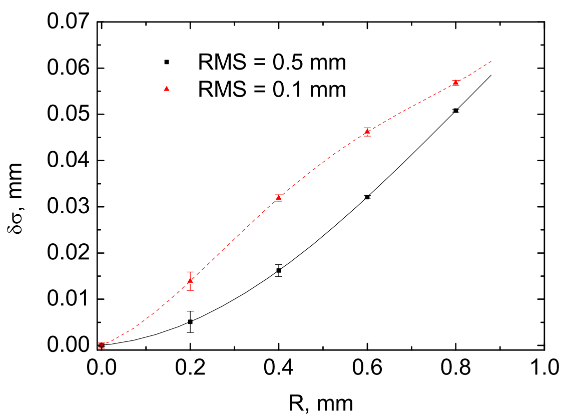

Figure 3: $\delta\sigma/\sigma$ as a function of the depth of focus.

below 2 mm in order to have uncertainty smaller than 10 %. For electrons with energy of 15 MeV the light cone from the OTR is 0.03 rad, this allows us to use depth of field values up to $\pm 3.3\,mm$. These restrictions allow us to use screens with $45°$ incidence angle.

CCD CAMERA

The main contribution to the uncertainty of the beamsize measurements with a CCD camera is the transformation of the image due to the discrete digital sampling of the amplitude signal from the chip. This effect becomes important when measuring beams with large halos. We can simulate a beam with halo by mixing two Gauss distributions with different weight and RMS size. In fig. 4 the projection of two Gauss distributions with a ratio between the weights of $1/10$ and two different ratios between the RMS sizes. The corresponding RMS sizes are $\sigma_{1/4} = 0.2\,mm$ and $\sigma_{1/16} = 0.1\,mm$. The resulting deviation from the initial RMS size is more than 10 % for the 8 bit case and less than 1 % for the other two.

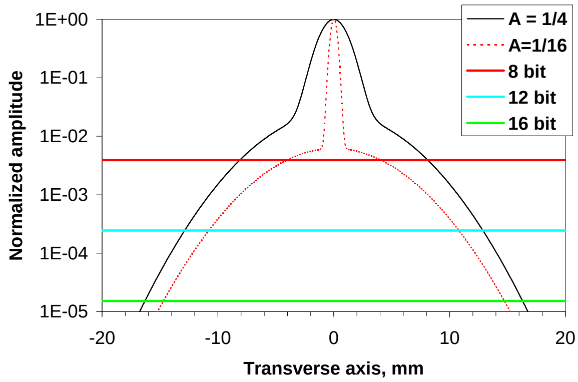

Figure 4: Projections of two mixed Gauss distributions together with the discrimination levels of 8, 12 and 16 bit.

CONCLUSIONS

We presented a detailed assessment of the systematic uncertainty associated with each of the above described components of the screen stations used at PITZ. Most critical parts of the screen station are the spatial resolution of the optical system and the digital resolution of the CCD camera. Still the interactions between effects from different components of the system are to be investigated.

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REFERENCES

[1] A. Oppelt et al., "Status of the PITZ Facility Upgrade", LINAC'06, Knoxville, USA, 2006.

[2] V. V. Paramonov et al., "DESGIGN PARAMETERS OF THE NORMAL CONDUCTING BOOSTER CAVITY FOR THE PITZ-2 TEST STAND, LINAC 2004, Lübeck, Germany, 2004.

[3] L. Staykov et al., "Commissioning of a New Emittance Measurement System at PITZ", FEL'06, Berlin, Germany, 2006.

[4] J. Roensch et al., "Measurement of the longitudinal phase space at the photo injector test facility at DESY in Zeuthen (PITZ)", DIPAC'05, Lyon, France, 2005.

[5] R. Spesyvtsev, "Transverse Beam Size Measurement Systems at Photo Injector Test Facility in Zeuthen", Diploma thesis, DESY/Karazin Kharkiv National University, 2006.

[6] GEANT collaboration, CERN/LHCC 98-44, GEANT4: "An Object Oriented Toolkit for Simulation in HEP"; see also website: http//wwwinfo.cern.ch/asd/geant4/geant4.html