SCINTILLATING SCREEN MONITORS FOR TRANSVERSE ELECTRON BEAM PROFILE DIAGNOSTICS AT THE EUROPEAN XFEL

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Abstract

Transverse beam profile diagnostics in modern electron linear accelerators as free electron lasers or injector linacs is mainly based on optical transition radiation (OTR) as standard technique which is observed in backward direction when a charged particle beam crosses the boundary between two media with different dielectric properties. The experience from modern linac based 4^{th} generation light sources shows that OTR diagnostics might fail because of coherence effects in the OTR emission process. As consequence, for the European XFEL which is currently under construction in Hamburg, transverse beam profile measurements are based on scintillating screen monitors. The LYSO:Ce screens are oriented such that coherent OTR generated at the screen boundaries will geometrically be suppressed. An additional feature is that the imaging optics operates in Scheimpflug condition, thus adjusting the plane of sharp focus with respect to the CCD chip, and significantly increasing the apparent depth of field. This report gives an overview of the measuring principle and the monitor setup together with results of laboratory test measurements and a first prototype test at FLASH.

INTRODUCTION

Optical transition radiation (OTR) monitors are standard tools for the measurement of transverse beam profiles in electron linacs. Unfortunately, micro–bunching instabilities in high–brightness electron beams of modern linac–driven free–electron lasers (FELs) can lead to coherence effects in the emission of OTR [1]. Thus, in these cases it is not possible to use OTR to obtain a direct image of the electron beam. As a result, for the European XFEL it was decided to use scintillation screens for transverse beam profile measurements [2, 3]. The required resolution is 10 μm over the entire field–of–view (FOV). A series of experiments was performed to study the performance of different types of scintillators as a function of material property, thickness and the observation geometry [4, 5]. Based on these results it was decided to use 200 μm thick LYSO:Ce and to observe the scintillator under an angle of 45 deg with respect to the beam axis. In order to minimize depth–of–focus effects, the Scheimpflug principle was applied for the optical layout of the monitor [6]. In the subsequent sections, the monitor setup is described together with results of test measurements in the laboratory and a first beam measurements at the VUV free–electron laser FLASH (DESY, Hamburg).

MONITOR LAYOUT

Figure 1 gives an overview of the monitor which is composed of three basic components: the vacuum chamber, the mover, and the optic box. The mover is used to precisely position the target, consisting of scintillation screens and a test chart for calibration purposes, via a stepper motor.

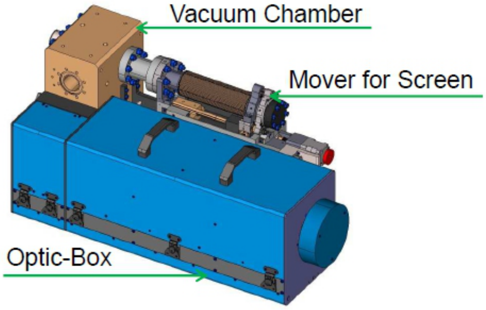

Figure 1: Basic components of a screen station.

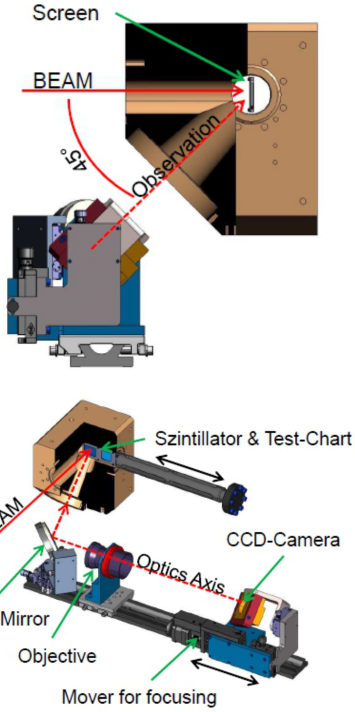

Figure 2: Observation geometry of 45 deg with respect to the beam axis (top) and layout of the imaging optics (bottom).

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Figure 2 (top) illustrates the screen inserted in the vacuum chamber. Observation of the screen is performed under an angle of 45 deg. The imaging optics (bottom) consists of a tilted mirror, an objective lens and a CCD camera (Basler aviator avA2300-25gm). The camera with a pixel size of 5.5 μm × 5.5 μm is mounted onto a motorized mover used for remote adjustment of the focusing distance. An important prerequisite for the CCD selection was the requirement of a large chip size of 1 inch, thus allowing to observe electron bunches moving in a certain distance away from the nominal beam axis without additional need to use different optical magnifications. In order to correct perspective distortion caused by the 45 deg observation geometry over the whole CCD chip, the Scheimpflug principle is applied. This principle states that a planar object (scintillation screen) which is not parallel to the image plane (CCD chip) will be completely in focus if the extended object-, lens- and image planes will intersect in one line. Furthermore the CCDs are used without cover–glass and microlens–array. This helps to minimize the mis–registration of light rays in adjacent pixels due to imperfect imaging of the lenslet array which is caused by the CCD tilt angle required for the Scheimpflug principle. Two monitor versions with different optical magnifications of 1:1 and 1:2 are in use for the XFEL.

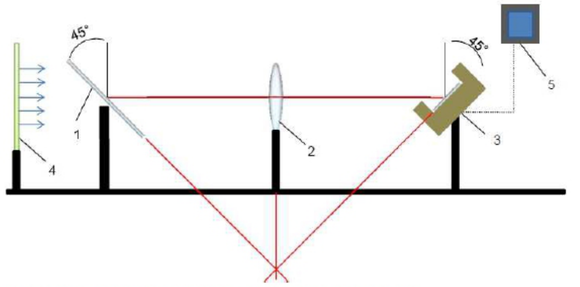
LABORATORY TEST MEASUREMENTS

A series of test measurements was carried out in order to investigate the resolution requirement of 10 μm which are described in the following.

Scheimpflug Geometry under 45 Degree

The goal of the first measurement was to verify that the required resolution can be achieved with the design components for the monitor. To do so, a dot grid pattern was imaged onto the CCD with a magnification of 1:1 in linear observation geometry, see Fig. 3.

For the determination of the local resolution along the CCD chip, the steepness of the bright/dark–transition was analyzed for each dot, see Fig. 4. This resolution averaged over the entire CCD chip amounted to 5.4 μm which is far below the required resolution of 10 μm.



[1] Dot Grid Target [by Edmund, spot diameter 0.50mm]
[2] Macro Objective [by Schneider-Kreuznach, f = 180mm]
[3] CCD-Camera [by Basler, aviator avA2300-25gm, without microlens-array and cover glass]
[4] Lighting
[5] Computer for analysis

Figure 3: Sketch of the Scheimpflug test measurement setup in linear geometry.

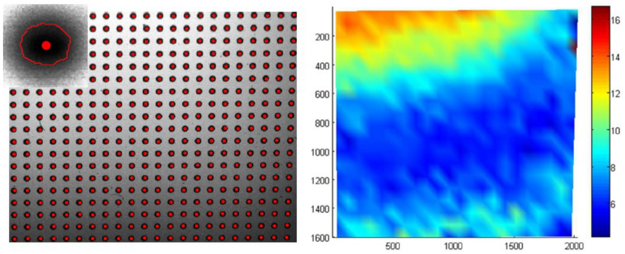


Figure 4: The recorded dot grid pattern (left) with a single dot. For each dot, the steepness of the transition was analyzed resulting in a local resolution (right).

Resolution Measurement in Monitor Chamber

In the next laboratory measurement, the resolution was studied in the monitor chamber itself (c.f. Fig. 2 bottom), taking into account the light deflection by the tilted mirror. Measurement and analysis were performed as before, i.e. a dot grid pattern was mounted at the screen position and imaged onto the CCD oriented in Scheimpflug geometry. Figure 5 shows the local resolution along the CCD chip, resulting in a mean resolution of 10.5 μm which is in very good agreement with the requirement of 10 μm.

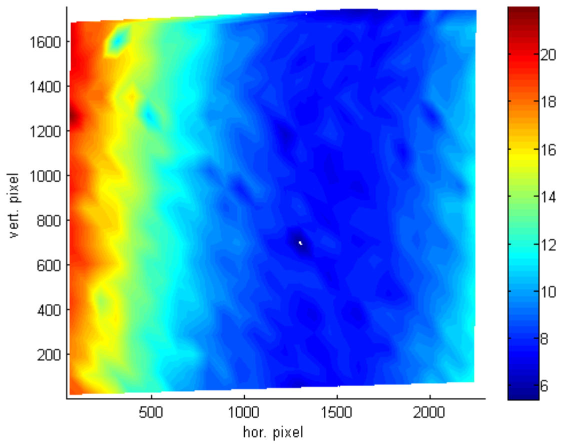


Figure 5: Local resolution along the CCD chip as measured in the screen monitor chamber using a dot grid pattern.

PROTOTYPE TEST

Finally, a prototype of the complete monitor setup was tested under realistic conditions with the electron beam of the VUV–FEL FLASH (DESY, Hamburg). The monitor was installed in a test dump section for single bunch operation, and beam profiles were recorded at a beam energy of

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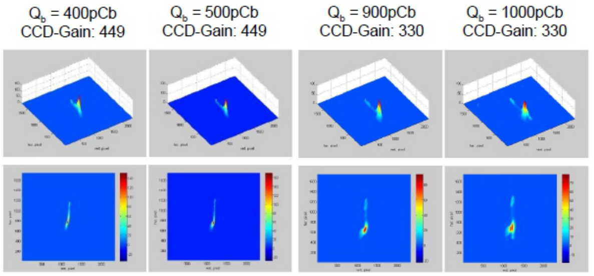

Figure 6: Beam profile images, measured for bunch charges of 400 pC, 500 pC, 900 pC and 1 nC (from left to right).

685 MeV and bunch charges between 50 pC and 1 nC.

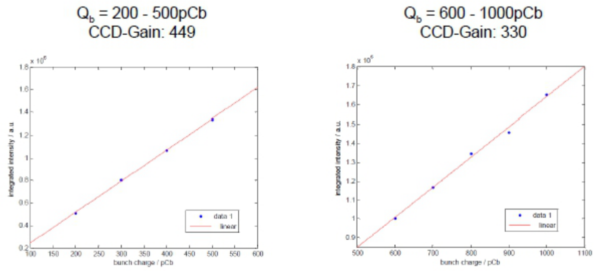

Figure 7: The integrated intensity versus bunch charge for two different CCD gain settings.

In the first series of measurements, the linearity of the monitor was investigated by varying the bunch charge. Figure 6 shows typical beam images which were taken for different bunch charges. For the data analysis, the recorded intensities in each image were integrated over the whole CCD chip, and the resulting integrated intensities were plotted as function of the bunch charge as shown in Fig. 7. As result, it is concluded that the monitor shows a clear linear behavior over the whole range of bunch charges at this beam spot size.

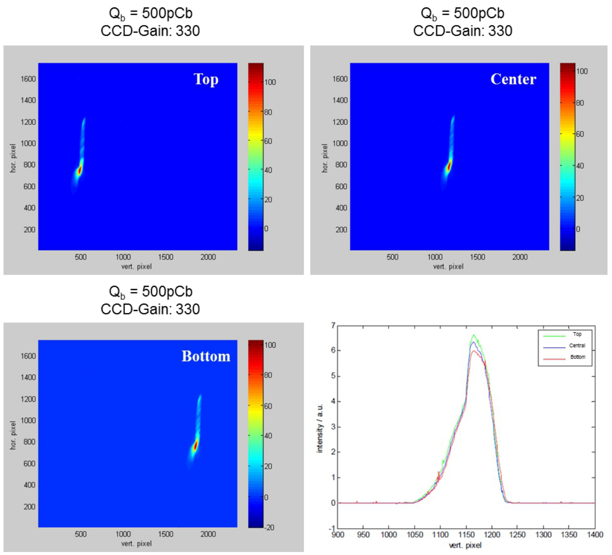

Figure 8: Beam spots recorded at three different electron beam positions at the scintillator screen (images rotated by 90 deg) and a comparison of the vertical beam projections. No profile broadening or distortion can be observed.

As next step, the quality of the Scheimpflug geometry was tested. To do this, the vertical electron beam position was varied at the location of the LYSO:Ce screen by changing the settings of an upstream corrector dipole magnet. Figure 8 shows examples of measured beam spots for different electron beam positions (images rotated by 90 deg) together with a comparison of the vertical projections. As can be seen from this comparison, it is not possible to observe any beam profile broadening or distortion, thus demonstrating that the Scheimpflug imaging works well in this monitor setup.

In the last step, an upper limit for the achievable monitor resolution was deduced. For this a slice was made through a recorded beam spot, see Fig. 9. As can be seen, a beam size of about 22 μm is clearly visible. Therefore beam sizes in the order of 50 μm as expected for the XFEL can easily be measured.

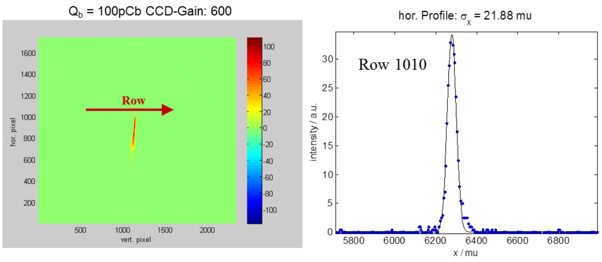

Figure 9: Left: structure of the beam spot as measured at a bunch charge of 100 pC together with the slice for resolution analysis. Right: evaluation of the slice profile.

SUMMARY AND CONCLUSION

A screen monitor has been designed for the XFEL with a resolution of 10 μm over a large field of view. A series of test measurements has been performed to verify the design goals and to study the influence of design decisions on the resolution. Measurements performed in the laboratory to study the optical resolution under a Scheimpflug geometry with an observation angle of 45 deg indicate a resolution of 5.4 μm which is far below the required 10μm.

Subsequent measurements with the complete monitor setup and a tilted mirror show negligible degradation of the resolution, even considering the rather large Scheimpflug angle.

A prototype test has been performed at FLASH under realistic beam conditions to study the linearity of the monitor as well as the image properties of the Scheimpflug geometry. The linearity clearly indicates that scintillator and CCD camera are not in saturated in the range of investigation. The Scheimpflug imaging properties investigated at different beam positions at the scintillator screen show no beam

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distortion. As an upper guess, the effective resolution of the monitor including the scintillator screen is better than 22 μm, thus render it possible to resolve transverse electron beam profiles as expected for the XFEL. The final design, construction and serial production of the screen stations for the European XFEL is presently underway at DESY.

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