DEVELOPMENT OF SCREEN MONITOR WITH A SPATIAL RESOLUTION OF TEN MICRO-METERS FOR XFEL/SPring-8

K. Yanagida*, H. Tomizawa and A. Yamashita, JASRI, XFEL Joint Project /SPring-8
1-1-1 Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5198
S. Inoue and Y. Otake, RIKEN, XFEL Joint Project /SPring-8
1-1-1 Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5148

Abstract

A screen monitor with a resolution of less than 10 μm was developed for XFEL/SPring-8. It comprises a vacuum chamber with a metal (100 μm, SUS) foil to emit OTR, a lens for focusing and a CCD camera system. In order to realize this resolution, the lens is placed close to the foil, the distance between the lens and the foil is 100 mm, and the lens has a large diameter (2 in.). This optical-geometrical structure contributes much to increase the numerical aperture of a near-field image. Although the range of the observation wavelength is wide, such as from 400 to 800 nm, a resolution of 2.5 μm on the foil surface has been calculated. The experimental data of the developed optics also suggested the same resolution.

INTRODUCTION

At SPring-8, the 8-GeV linac for an X-ray free electron laser (XFEL) is now under construction. In order to realize the XFEL, highly qualified electron beams are required. Especially in the undulator section the beam should have a size of several tens of micro-meters, a peak beam current of several kiro-amperes, a micro-bunch length comparable to the X-ray wavelength, and an emittance of less than 1 πmm·mrad [1].

In order to tune and realize such a beam, beam monitors are very important, and should have a comparable resolution to the beam parameters mentioned above. For a screen monitor (SCM), the required resolution is less than 10 μm. To achieve this resolution we have developed a prototype SCM using OTR and fluorescence radiation, based on the following design concept.

Generally a CCD camera with a ready-made zoom lens is used for SCM measurements. In this case we cannot have a precise parameter of the lens, such as the curvature, broadband property of dispersion, Abbe's number of glass and so on. This means that we cannot evaluate characteristics like aberrations, magnification and effective focal length using an optical design program. Therefore, we decided to know all of the design parameters so that we can evaluate the characteristics of the optical system. Consequently, a lens with published optical parameters was chosen, or a lens produced optimally by using an optical design program was selected. This paper gives a summary of the prototype SCM with the lens developed for transverse spatial structure measurements with a resolution of less than 10 μm.

SYSTEM CONFIGURATION

Mechanical System

The mechanical part of the SCM comprises a vacuum chamber with radiators, motorized stages that change the positions of a lens and a CCD camera.

The vacuum chamber has a shaft that links the upper and lower slide stages, as shown in Fig. 1. There are three holes along the shaft: an aperture of the beam passage and holes for two kinds of radiators.

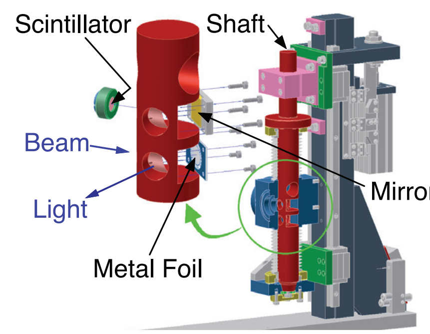

Figure 1: Structure around radiators.

One radiator is metal foil to emit OTR with a thickness of 100 μm. It is placed in the bottom hole where an electron beam hits the foil at an angle of 45°. The foil consists of nine apertured SUS foils (denoted by green foils in Fig. 2) and one SUS mirror foil without an aperture (denoted by the red foil in Fig. 2). The thickness of each foil is 100 μm. These ten foils are bonded by a diffusion bonding process, and form a single plate (see photograph in Fig. 2).

Figure 2: Metal foil.

The other radiator is a scintillator plate with a thickness of 100 μm, which is placed in the center hole where an electron beam hits the plate perpendicularly. The fluorescence from the plate is reflected at a mirror, and then led to the CCD camera.

* E-mail: ken@spring8.or.jp

The lens and the CCD camera are mounted on two different remote-controlled motorized stages. The position of the motorized stage with a lens is set for determining the magnification, and a motorized stage with a CCD camera is moved for focusing (see Fig. 3).

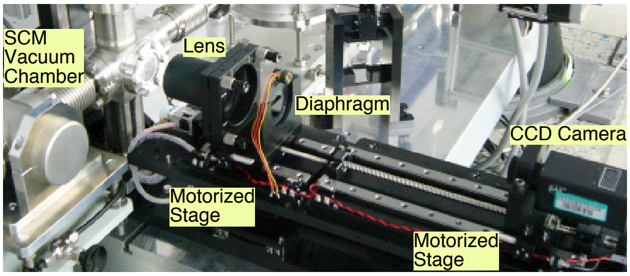

Figure 3: Developed prototype SCM installed in the SCSS test accelerator.

Optical System

In order to obtain a bright and high-resolution optical system, the lens is placed close to the radiator, the distance between the lens and the radiator is 100 mm, and the lens has a large diameter (2 in.). This optical-geometrical structure contributes much to increases the numerical aperture (NA) of a near-field image. Table 1 summaries the principal specifications of the optical system. These parameters were calculated by the optical design program Zemax (ZEMAX DEVELOPMENT CORPORATION).

The lens structure is to be simple, like four elements in three groups, so as to reduce reflection on the glass surface. These three groups are installed into a single tube for easy alignment of the light axis. The bandwidth of the observation wavelength is wide, such as from 400 to 800 nm. The reason for the wide bandwidth is to obtain high light intensity. To realize this wide bandwidth, anomalous dispersion glass is used for the lens.

Geometrical and chromatic aberrations are minimized to be as small as possible by our design to reach down to a diffraction limit at 4 magnifications. The pixel size of the CCD is smaller than the image size due to diffraction. This means that the resolution of this optical system depends only on the image size, due to diffraction (diffraction-limted system).

EVALUATION

In oder to evaluate the flatness of the metal foil, the positioning accuracy of the motorized stages and the resolution of the optical system following examinations were carried out.

Mechanical Evaluation

The surface of the metal foil was measured, and found to be slightly concave. The concave depth is 3 μm in an area of 5ϕ mm. This value corresponds to only a $\sim$1 mrad

Table 1: Principal Specifications of Optical System

Type of optical system	Object-space telecentric
Lens structure	4 elements in 3 groups
Lens diameter	50.8 mm
Lens effective focal length	85.0 mm
Pupil radius of diaphragm	1.0 $\sim$ 17.5 mm
M : Magnification	1.2 $\sim$ 4.0
Object-space NA at M = 4	0.010 $\sim$ 0.176
Field of view at M = 4	2.2 $\times$ 1.7 mm (H $\times$ V)
Wavelength	400 $\sim$ 800 nm
Resolution at object surface	2.5 μm (HWHM)

difference from the light axis to the CCD camera, and is thought to be negligibly small compared to the tolerance of the optical system.

When the motorized stages moved from a position at 1.2 magnifications to a position at 4 magnifications, the positioning accuracy was measured. Checking the accuracy was done by analyzing the image acquired by a CCD camera. A transverse displacement errors along the movements of the motorized stages for focusing and zooming were 20 μm in the horizontal direction and 150 μm in the vertical direction. The cause of the vertical displacement error was a deformation of the bread board that mounted the motorized stages on it. The vertical displacement is sufficiently small compared with the size of the field of view.

Optical Evaluation

The spacial resolution of the optical system was measured at 4 magnifications. A checking target used to evaluate the resolution is the Fixed Frequency Grid Distortion (FFGD) target (EDMUND OPTICS), as shown in Fig. 4. The diameter of dots on the target is 62.5 μm, and the center-to-center spacing of the dots is 125 μm.

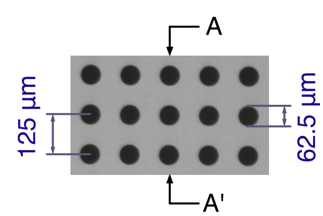

Figure 4: Pattern of the FFGD target.

In Fig. 5 the black line denotes the intensity proportional to contrast along the A-A' line in Fig. 4. The blue line expresses the differential of the intensity. The differential gives the resolution of the optical system. The HWHM (half width at half maximum) value of the differential data is 9.9 μm (2.5 μm on the object surface). This value is almost the same as the resolution calculated by Zemax.

BEAM TEST

At the SCSS test accelerator [2], 250-MeV electron beams were targeted on the metal foil to observe the near-

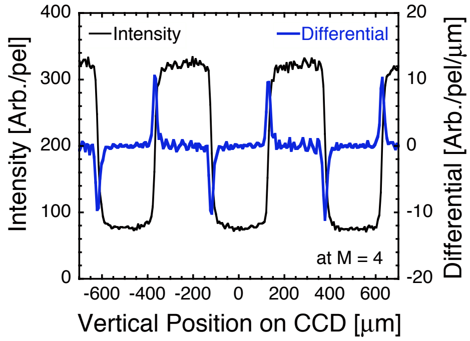

Figure 5: Intensity along the A-A' line in Fig. 4 and its differential.

field images of OTR at 4 magnifications. The images were analyzed to evaluate the image size of the OTR. This evaluation gives information on the resolution in the case of OTR emitted from an 8-GeV electron beam.

For the beam test, the electron beam size was kept minimized in the horizontal axis by quadrupole magnets, as shown in Fig. 6, and the numerical aperture (NA_O) of the object space was varied from 0.011 to 0.152 by changing the pupil radius. The measured image intensities and the horizontal image sizes are shown as circles in Fig. 7 and Fig. 8.

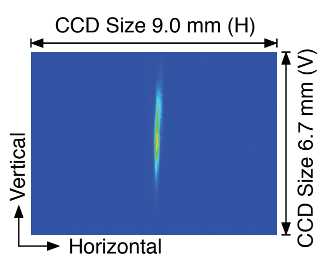

Figure 6: Near-field image of the OTR.

In order to compare the measured values and the theoretical ones, a calculation of the image intensity and the size of the OTR was carried out. The angular distribution of the OTR strength [3] is approximately expressed as

$$\frac{\theta^2}{(\gamma^{-2}+\theta^2)^2}\,, \tag{1}$$

where γ is the Lorentz factor. The image intensity was calculated by integrating Eq. (1) in an integral range specified by NA_O. In Fig. 7 the calculated image intensity is indicated by the line. The line and circles exhibit the same tendency.

With this optical system, an image is formed by diffraction, and an object (beam profile). The image due to diffraction was calculated as follows: divide the OTR distribution of Eq. (1) into many sliced elements, specified by NA_O, calculate the image size and intensity of each element and integrate the image sizes and intensities of all elements into one image. In Fig. 8 the solid line expresses the calculated image size due to only diffraction. The dashed line

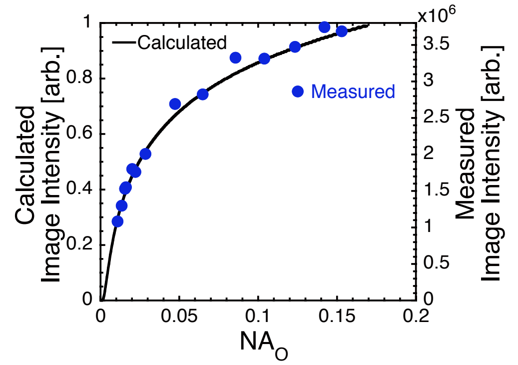

Figure 7: Measured and calculated image intensities.

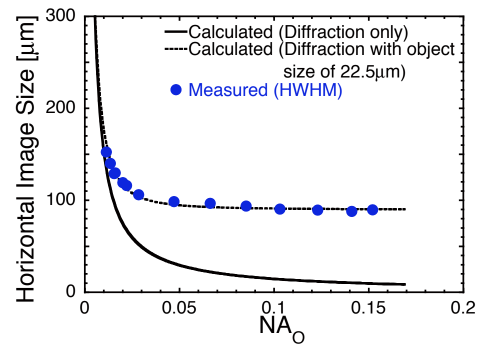

Figure 8: Measured and calculated horizontal image sizes.

expresses the root sum square of the calculated image sizes due to diffraction and an object with a size of 22.5 μm. The dashed line and the circles closely agree. This means that the electron beam size was surely measured down to 22.5 μm.

SUMMARY

The development of a screen monitor has been completed. The resolution of the screen monitor was calculated and measured with 2.5 μm in length on an FFGD target surface. This resolution is sufficient to measure the transverse spatial structure of beams in an undulator section. The screen monitor was also evaluated by observing OTR emitted from a beam on a metal foil surface at the SCSS test accelerator. We must therefore check weather our developed OTR radiator works or not. The OTR radiator actually emitted light. The electron beam size was surely measured down to 22.5 μm.

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