Physics Letters A ••• (••••) •••–•••

Contents lists available at SciVerse ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

New method for measuring beam profiles using a parametric X-ray pinhole camera

Y. Takabayashi *, K. Sumitani

SAGA Light Source, 8-7 Yayoigaoka, Tosu, Saga 841-0005, Japan

ARTICLE INFO

Article history:
Received 29 June 2013
Received in revised form 18 July 2013
Accepted 18 July 2013
Available online xxxx
Communicated by V.M. Agranovich

Keywords:
Parametric X-ray radiation
Pinhole
Beam profile

ABSTRACT

We propose a new method for measuring electron beam profiles using parametric X-ray radiation. In this method, a pinhole is placed between the source of parametric X-ray radiation and a two-dimensional X-ray detector, and the beam profile can be reconstructed on the detector, i.e., based on the principle of a pinhole camera. The profiles are in good agreement with the results obtained using a standard method with optical transition radiation. This method may prove useful to measure profiles of electron beams with short bunch lengths in recent advanced linear accelerators.

1. Introduction

The measurement of beam profiles is indispensable in the field of accelerators to determine the beam quality and condition of the accelerator, so that many methods have been developed to date. A fluorescent screen and a CCD camera comprises a simple setup that is often used to image profiles of a beam from a linear accelerator. For a more precise measurement, optical transition radiation (OTR) has been used instead of fluorescent light [1–4]. However, it was recently determined that OTR cannot be used as an electron beam profile monitor at linear accelerators for X-ray free electron lasers (XFEL), because OTR becomes coherent due to the microstructure within the short bunch length of the electron beam [5,6]. When OTR becomes coherent, the OTR intensity is no longer proportional to the beam intensity; therefore, the beam profile cannot be measured correctly. A similar effect is expected to occur when the beam size is smaller than the wavelength of visible light, e.g., at the international linear collider (ILC).

Therefore, the use of photons with shorter wavelengths is required to avoid such coherence [7–11]. Recently, we proposed that parametric X-ray radiation (PXR) could be used to monitor beam profiles [11]. PXR is produced in the Bragg direction when a relativistic charged particle is incident on a single crystal, and this radiative process can be regarded as the diffraction of virtual photons associated with the incident particle. Since its first theoretical prediction [12], there have been extensive theoretical and experimental studies on PXR [13–17]. PXR has also been applied as a tunable monochromatic X-ray source for many studies, such as X-ray imaging [18,19].

In Ref. [11], we proposed two approaches: the local method and the remote method. In the local method, a two-dimensional X-ray detector is placed close to the target and measures the PXR profile. In this case, the PXR profile mainly reflects the beam profile, so that the beam profile can be extracted from the PXR profile by a deconvolution step. We demonstrated a proof-of-principle experiment for the local method in Ref. [11]. For the remote method, we proposed the use of a Fresnel zone plate (FZP) as an X-ray lens and designed the corresponding experimental setup. In this method, the X-ray detector is placed far from the target, and the beam profile at the target is focused on the X-ray detector using the FZP. Although FZPs have high position resolutions (down to ca. 10 nm) [20,21], they are expensive and their precise alignment is required in the experimental setup.

In this Letter, we propose to use a pinhole to measure electron beam profiles instead of a FZP, based on the principle of the pinhole camera. A pinhole is placed between the PXR source and the X-ray detector, and a beam profile can be reconstructed on the X-ray detector by X-rays that pass through the pinhole. A similar method is often employed as a profile monitor for the electron beam of a storage ring using synchrotron radiation X-rays from the electron beam, and beam sizes in the order of 10 μm are obtained [22]. In the case of the X-ray pinhole camera, the position resolution is limited to ca. 10 μm due to the diffraction effect of X-rays by the pinhole (see, e.g., [23,24]). Although the position resolution of this method is lower than that of the FZP method, and the PXR yield is restricted by the small size of the pinhole, a pinhole can be

* Corresponding author. Tel.: +81 942835017; fax: +81 942835196.
E-mail address: takabayashi@saga-ls.jp (Y. Takabayashi).

0375-9601/$ – see front matter
http://dx.doi.org/10.1016/j.physleta.2013.07.035

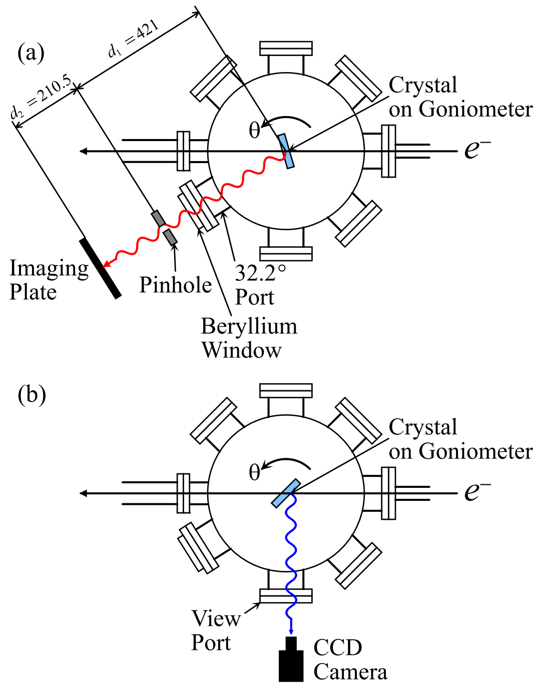

Fig. 1. Schematic diagram of the experimental setup for beam profile measurements using (a) PXR and (b) OTR.

easily prepared and handled. Therefore, the "PXR pinhole camera" would be useful as an alternative method to measure beam profiles.

2. Experimental

Fig. 1(a) shows a schematic diagram of the experimental setup. Experiments were performed using a 255 MeV electron beam from a linear accelerator at the SAGA Light Source (SAGA-LS) [25]. The SAGA-LS is a synchrotron radiation facility, and the linear accelerator is used as an injector to the SAGA-LS storage ring. The repetition rate of the beam acceleration in the linear accelerator was 1 Hz and the average beam current was ca. 7 nA. A 20 μm thick Si crystal with the ⟨001⟩ crystallographic axis perpendicular to the crystal surface was mounted on a two-axis goniometer in a vacuum chamber and the crystal was set so that the (220) plane was vertical. The rotation angle around the vertical axis was defined as θ, where $\theta = 0°$ corresponds to the normal incidence condition. The horizontal and vertical angular divergences of the incident beam were $\sigma'_{i,x} = 0.2$ mrad and $\sigma'_{i,y} = 0.3$ mrad, respectively, where σ represents one standard deviation. The multiple scattering angle of the incident electrons in the target, which is averaged over the path length in the target, is estimated to be $\sigma'_{MS} = 0.35$ mrad [26]. Accordingly, the angular spread of the electron beam can be calculated as $\sigma'_{beam,s} = \sqrt{\sigma'^2_{i,s} + \sigma'^2_{MS}}$ ($s = x$ or y); $\sigma'_{beam,x} = 0.40$ mrad and $\sigma'_{beam,y} = 0.46$ mrad.

The crystal was rotated by $\theta = 16.1°$, and the (220) reflection of the PXR produced around 32.2° was extracted through a 250 μm thick beryllium window. In this case, the Bragg energy was calculated to be 11.6 keV. A 2 mm thick tungsten plate with a 200 μm diameter pinhole was placed at a distance of $d_1 = 421$ mm from the target. A two-dimensional X-ray detector was placed at a distance of $d_2 = 210.5$ mm from the pinhole. The magnification of this pinhole camera setup is determined to be $M = d_2/d_1 = 0.5$. A 200 × 200 mm^2 imaging plate was adopted as an X-ray detector. Imaging plates offer advantages such as high position resolution, high linearity of intensity (dynamic range: 10^5), and flexibility for

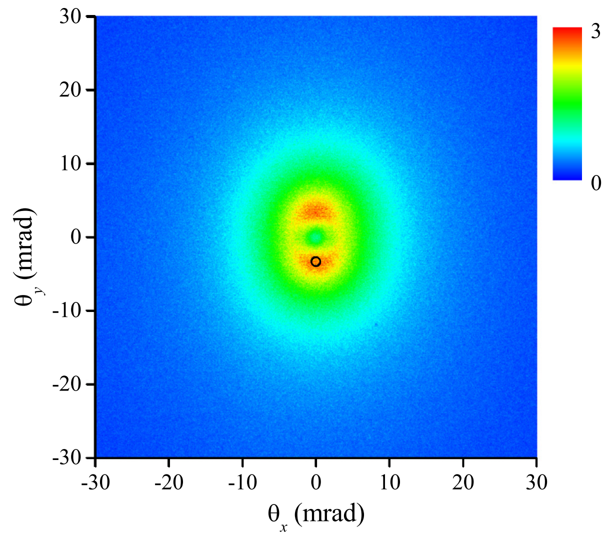

Fig. 2. PXR angular distribution obtained without the pinhole installed. The circle indicates the angular position of the pinhole installed in later experiments. Note that the size of the pinhole is not scaled.

use [27,28]. The position resolution of the imaging plate was estimated to be $\sigma_{IP} = 48$ μm [29].

For comparison, beam profiles were also measured using OTR. The OTR does not become coherent for the SAGA-LS linear accelerator. A schematic diagram of the experimental setup for OTR is shown in Fig. 1(b). As an OTR screen, the same Si crystal as that for the PXR experiments was employed. The surface of the crystal was mirror-polished for the efficient production of OTR. The crystal was rotated by $\theta = -45°$ and the OTR emitted in the 90° direction from the target surface was extracted through a view port. The profiles were imaged with a CCD camera. To evaluate the position resolution of the CCD camera (including the contribution of the CCD camera lens), the sharp edge of a plate at the target position was imaged; the position resolution was evaluated to be $\sigma_{CCD} = 125$ μm from the blurring of the edge. A comparison with the PXR experiments is presented later.

3. Results

Fig. 2 shows the PXR angular distribution obtained without the pinhole plate installed, where $\theta_s = s_{IP}/(d_1 + d_2)$, $s = x$ or y, and x_{IP} and y_{IP} are the horizontal and vertical positions on the imaging plate, respectively. The Bragg direction corresponds to $\theta_x = \theta_y = 0$. The intensity is in arbitrary units. The measurement time was 600 s. A cone-like structure typical of PXR was clearly observed. Ref. [29] gives a comparison of the observed angular distribution with the theoretical distribution and a detailed discussion. After this measurement, the pinhole was placed at the peak position of the PXR angular distribution, which is indicated by a circle in Fig. 2.

Fig. 3(a) shows a beam profile obtained using PXR, where the positions were converted as $s = s_{IP}/M$, taking into account the magnification, M. The peak position was defined as $x = y = 0$. The intensity is in arbitrary units and the background level was ∼ 1.0. The measurement time was 12 600 s, i.e., the beam profiles were integrated over 12 600 beam shots. Fig. 3(b) shows a beam profile obtained using OTR. The intensity is in arbitrary units and the background level was close to 0. This image was acquired in 1 beam shot. The PXR image is in good agreement with the OTR image, including the asymmetry of the profile.

For more detailed comparison, we plotted the beam profiles projected onto the horizontal and vertical planes in Figs. 4(a) and 4(b), respectively. The background was subtracted and the peak