INVESTIGATION OF THE APPLICABILITY OF PARAMETRIC X–RAY RADIATION FOR TRANSVERSE BEAM PROFILE DIAGNOSTICS

G. Kube, C. Behrens, DESY, Hamburg, Germany
A.S. Gogolev, Yu.P. Popov, A.P. Potylitsyn, Tomsk Polytechnic University, Tomsk, Russia
W. Lauth, Institut für Kernphysik, Mainz, Germany
S. Weisse, DESY, Zeuthen, Germany

Abstract

Optical transition radiation (OTR) which is observed in backward direction when a charged particle beam crosses the boundary between two media with different dielectric properties is widely used as standard technique for transverse beam profile diagnostics in electron linacs. The experience from modern linac based light sources like LCLS or FLASH shows that OTR diagnostics might fail because of coherence effects in the OTR emission process. A possibility to overcome this limitation is to measure at much shorter wavelengths, i.e. in the X-ray region, using parametric X-ray radiation (PXR) which additionally offers the advantage to be generated at crystal planes oriented under a certain angle to the crystal surface, thus allowing a spatial separation from a possible coherent OTR background. A first test experiment has been performed at the Mainz Microtron MAMI in order to study the applicability of PXR for beam diagnostics, and status and results of this experiment are reported.

INTRODUCTION

Transverse beam profile diagnostics in electron linacs is widely 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. Unfortunately, microbunching instabilities in high–brightness electron beams of modern linac–driven free–electron lasers (FELs) can lead to coherence effects in the emission of OTR, thus rendering it impossible to obtain a direct image of the particle beam and compromising the use of OTR monitors as reliable diagnostics for transverse beam profiles. The observation of coherent OTR (COTR) has been reported in the meantime by several facilities [1, 2].

In order to allow beam profile measurements in the presence of microbunching instabilities, different monitor concepts are under consideration. Besides the usage of inorganic scintillation screens [3, 4, 5], an option to suppress coherence effects is to measure at smaller observation wavelengths. While Ref. [6] reported about the first beam profile imaging with transition radiation in the EUV region, the authors of the present report discussed the possibility to measure beam profiles in the X–ray region with parametric X–ray (PXR) radiation in Ref. [7].

PXR is emitted when a relativistic charged particle beam crosses a crystal, and the radiation process can be understood as diffraction of the virtual photon field associated with the particles at the crystallographic planes. As result, radiation is emitted in the vicinity of directions satisfying the Bragg condition. Besides the smaller radiation wavelength, the usage of PXR is advantageous because it is emitted from crystallographic planes inside the radiator which usually have a certain inclination angle with respect to the crystal surface, thus allowing a spatial separation from a possible COTR background which is directly generated at the surface. Disadvantage is the PXR radiation yield which is typically 1 – 2 orders of magnitude smaller than the one from transition radiation. However, this disadvantage might be compensated by a simplified setup compared to an EUV beam profile monitor which requires an in–vacuum installation because of the strong absorption in matter.

Based on experimental schemes proposed in Ref. [7], a test experiment has been performed in order to investigate the possibility to use PXR for transverse beam profile measurements, and first results are presented in this report. In a recent publication, the applicability of PXR for beam diagnostics was investigated independently by using a 255 MeV electron beam and a 20 μm thick Si crystal [8].

THEORETICAL CONSIDERATION

PXR can be interpreted as Bragg reflection of the virtual photon field associated with the particles at the crystallographic planes. Since its first observation [9], detailed studies were performed both theoretically and experimentally, see e.g. [10] and the references therein. Therefore, in the following only the PXR characteristics of importance for beam diagnostics are discussed.

The PXR photon energy is determined by the experimental parameters in the following way

$$\hbar\omega = \hbar c \, \frac{|\vec{\beta}\cdot\vec{\tau}|}{1-\sqrt{\varepsilon}\,\vec{\beta}\cdot\hat{k}} \tag{1}$$

with $\vec{\beta} = \vec{v}/c$ the vector of the reduced electron velocity, $\vec{\tau}$ the reciprocal lattice vector, $\hat{k}$ the direction of the wave vector, and ε the crystal dielectric constant which is in the order of 1 for X–rays, see also Fig. 1. The angular distribution of PXR has a double–lobe structure similar to transition radiation with a characteristic opening angle of

$$\Delta\theta = \sqrt{\left(\frac{1}{\gamma}\right)^2 + \left(\frac{\hbar\omega_p}{\hbar\omega}\right)^2}\,. \tag{2}$$

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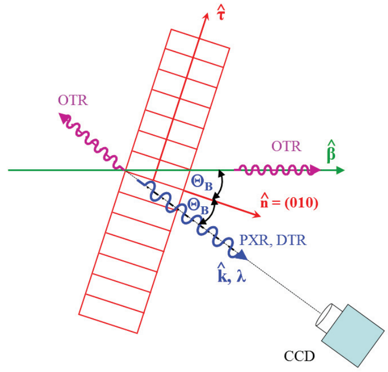

Figure 1: Sketch of the experimental setup.

Here γ is the Lorentz factor and $\hbar\omega_p$ the plasma energy of the crystal which amounts to 31 eV in case of silicon.

Keeping in mind that it is the PXR angular distribution which in principle acts as a point spread function and therefore defines the resolution of a transverse beam size monitor, their width should be kept as small as possible. While inspecting Eq. (2) one can directly see that $\Delta\theta$ decreases with increasing photon energy, with the angular width of OTR amounting $1/\gamma$ as limiting case. From Eq. (1) it follows that high photon energies are generated for small observation angles $\Theta_o = 2\,\Theta_B$, i.e. in the experiment the spatial resolving detector should be placed as close as possible with respect to the beam axis.

EXPERIMENTAL SETUP

Figure 1 shows a sketch of the experimental setup. The experiment was performed at the 855 MeV beam of the Mainz Microtron MAMI (University of Mainz, Germany) [11] in the beamline of the X1 collaboration. The beam was operated in cw mode with a mean beam current of about 0.5 μA. The target which consisted of a 50 μm thick (100)–cut silicon crystal was mounted onto a motorized stage which allowed a precise alignment of the crystallographic planes with respect to the beam axis. In the experiment the crystal was aligned in Laue geometry in two orientations for the observation of the (220) and the (400) reflex family. In order to achieve the narrowest angular distribution resp. the highest photon energies, the detector was placed under the smallest achievable observation angle of Θ_o = 22.5 deg which corresponds to PXR photon energies of $\hbar\omega_{220}$ = 16.55 keV resp. $\hbar\omega_{400}$ = 23.40 keV. The distance between target and detector amounted about 350 mm. As detector, a compact X–ray camera was used (ProxiVision HR25 X–Ray) which was based on a conventional analogue camera (Sony XC-ST70CE) with a P43 phosphor coating and fiber optics taper in front of the CCD chip, resulting in a spatial resolution of about 30 μm [12]. However, due to the 0.5 mm thick aluminum CCD input window, about 53% (24%) of the incoming PXR intensity was absorbed for the 220 (400) reflex. With a second CCD detector, mounted in backward direction under an angle of 22.5 deg, it was possible to perform measurements based on OTR which was generated at the entrance side of the crystal, thus allowing to record OTR beam profiles under the same experimental conditions.

Measurements of the PXR angular distribution were performed for 6 different beam configurations with horizontal (1σ) beam sizes between 40 μm and 260 μm, and vertical sizes between 40 μm and 800 μm.

Besides the experiment depicted in Fig. 1 and described before, a second setup for direct PXR imaging was used. In this setup, a LYSO:Ce scintillator was mounted in close distance from the PXR crystal, thus testing a direct conversion of X–rays in visible light and allowing the use of a conventional optical CCD. However, due to the weak coupling between CCD and scintillator the recorded intensities were so small that no beam spots could be recognized.

MEASUREMENT AND RESULTS

For each individual measurement 100 beam images were taken together with background images. The mean background was subtracted from the corresponding mean signal image, resulting in a background corrected beam spot. After this correction, a median filter was applied in order to remove the remaining salt and pepper noise originating from high energetic background interaction in a single pixel.

In Fig. 2 measured angular distributions are shown for the (220) reflection with 16.55 keV photon energy and two different beam sizes. As one can see from the left plot, a double lobe structure is visible which is a characteristic signature for radiation associated with the charged particle virtual photon field as it is the case for transition and PXR radiation. Furthermore, a comparison of these two recorded images shows that the size of the measured distribution depends on the size of the electron beam which indicates that a measurement of the angular distribution is sensitive on the beam size.

Figure 3 shows the same measurements, but this time for the (400) reflex with 23.40 keV photon energy. A direct comparison with the previous measurements for the (220) reflection indicates that the measured angular distributions are indeed smaller for higher photon energies as expected from theory, c.f. Eq. (2).

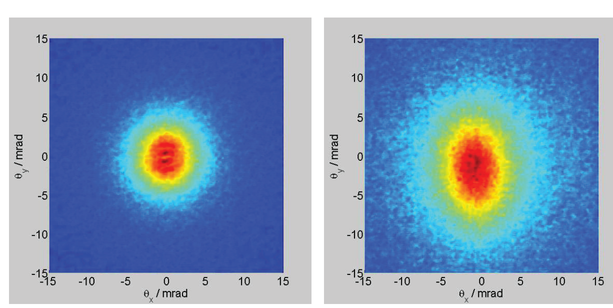

Figure 2: Measurement of the PXR angular distribution for the (220) reflex. Left: beam size σ_x = 45.7 μm and σ_y = 42.9 μm, right: σ_x = 44.7 μm and σ_y = 796 μm.

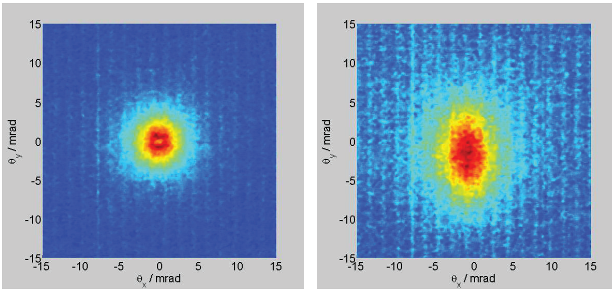

Figure 3: Measurement of the PXR angular distribution for the (400) reflex. Left: beam size σ_x = 45.7 μm and σ_y = 42.9 μm, right: σ_x = 44.7 μm and σ_y = 796 μm.

For better comparison, central vertical cuts normalized to the maximum intensity for both reflections and the small vertical beam size are shown in Fig. 4. From this comparison it is obvious that the lobes from the (400) reflection coincide with the central ones from the (220) reflection at angles of $\theta_y = \pm$ 0.6 mrad which is in contradiction to Eq. (2). Furthermore, the (220) angular distribution shows two additional lobes at angles of about $\theta_y = \pm$ 1.8 mrad. This observation is interpreted such that the central part of the measured distributions is either originating from higher–order diffracted PXR, or from diffracted transition radiation (DTR) which is generated at the entrance side of the crystal and Bragg reflected under the same angles than PXR.

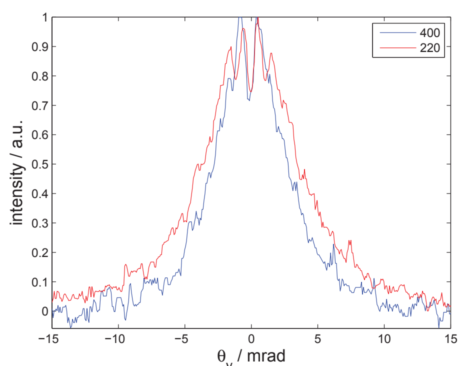

Figure 4: Central vertical cuts normalized to the maximum intensity for the (220) and the (400) reflection. The data were obtained from the measurements shown in Figs. 2 and 3 for the beam size σ_x = 45.7 μm, σ_y = 42.9 μm, and θ_x = 0 mrad.

At 855 MeV beam energy, the DTR opening angle of $\sim \gamma^{-1}$ agrees well with the observed one of 0.6 mrad. Moreover, the smearing out of the central minimum could be explained due to diffracted Bremsstrahlung (DBS) which has a central maximum. The additional lobes visible in the angular distribution of the (220) reflection are interpreted as PXR which has a wider distribution with an opening angle of about 2 mrad. In case of the (400) reflection, the PXR contribution to the total intensity seems to be reduced, and no additional lobes are visible.

SUMMARY AND CONCLUSION

In this report, investigations of PXR in view of possible transverse beam profile diagnostics are presented. Measurements with two different crystallographic reflections were carried out at an ultrarelativistic beam energy of 855 MeV, and X–ray reflexes were found at 16.55 keV and at 23.40 keV photon energy. The measured angular distributions show a dependency on the electron beam size, thus in principle allowing to extract information about the transverse beam profile. A preliminary analysis of these distributions indicates that not only PXR was emitted from the crystal, but in addition radiation components with narrower opening angles significantly contributed to the measured intensities. These additional radiation contributions can be interpreted as higher–order diffracted PXR, DBS, or DTR originating from the crystal entrance surface and Bragg reflected by the crystallographic planes, an effect already observed elsewhere [13].

In the nearest future, the data will be analyzed in detail in order to better understand and disentangle the individual radiation contributions. Based on these results it will be tested to extract information about the transverse beam profile from the angular distributions, and for future experiments an optimization in view of radiation intensity and resolution will be performed.

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