A possibility of transverse beam size diagnostics using parametric X-ray radiation

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Abstract. A method of transverse beam size diagnostics with μm space resolution by parametric X-ray radiation is proposed.

1. Introduction
Transverse beam profile diagnostics in modern electron linear accelerators as FELs 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. However, the experience from modern linac based light sources shows that OTR diagnostics might fail even for high energetic electron beams because of Coherent OTR emission (COTR). A cause of this emission is the micro-bunching instability, i.e. some unstable micro structures in the electron bunch that compromise the use of OTR monitors as reliable diagnostic scheme.

One possibility to overcome this limitation is to measure at much shorter wavelengths than the visible spectral region, i.e. in the X-ray range. In this contribution it is proposed to use a technique based on the observation of parametric X-radiation (PXR) for beam imaging. Besides the usability in this wavelength region, PXR offers the advantage to be generated at crystal planes oriented under a certain angle to the crystal surface, i.e. OTR and PXR are not reflected in the same direction which allows a spatial suppression of the COTR background.

In the proposed detection scheme a two-dimensional X-ray detector with μm space resolution is placed in the vicinity of a crystalline target that allows to measure a beam profile with transverse sizes down to σ ~ 10 μm. The detector is situated under a large angle with respect to the beam which offers the possibility to obtain an image of the electron spot with a small distortion if the distance L between target and detector is small (L/γ ≤ σ with γ the Lorentz factor).

2. Simulation
Parametric X-ray radiation (PXR) is emitted by a fast charged particle in a crystal due to diffraction of its virtual-photon field on crystallographic planes. PXR has been theoretically predicted [1–3] and then observed and studied with electron beams at different energies [4, 5].

The energy of PXR photons is determined by the experimental setup in the following way

\[ E_n = n \hbar \omega_n = \frac{2\pi hc}{d} \frac{\beta \sin \theta_B}{1 - \sqrt{E \beta \cos \theta_D \cos \theta_y}} \]
with the diffraction order, \( d \) the inter-planar distance, \( \beta = \frac{v}{c} \), \( \varepsilon \) the dielectric constant of the target material (\( \varepsilon \approx 1 \) for X-rays), \( \theta_B \) is the orientation (Bragg) angle of the crystal planes with respect to the particle momentum, and \( \theta_D \) and \( \theta_Y \) the radiation emission angles. The direction of the PXR maximum is determined by the angle \( \theta_D = 2\theta_B \) in the diffraction plane, and inclined to the diffraction plane at the angle \( \theta_Y(\omega) = \frac{\gamma^2}{\gamma^2 + (\omega_p/\omega)^2} \) with \( \gamma \) is the Lorentz factor and \( \hbar \omega_p \) the plasmon energy which amounts 31 eV for silicon. The diffraction plane is determined by the particle momentum and by vector normal to the crystal planes.

Calculations of the PXR characteristics from 855 MeV electrons in a Si (010) crystal of 10 µm thickness in Laue geometry have been performed according to the kinematic theory [6] by the algorithm described in the [7]. The results of these calculations will be presented in the following for two possible observation geometries and discussed in view of a possible particle beam diagnostics application.

2.1. Observation angle 90 degree

The sketch of the experimental setup of the proposed geometry is shown in figure 1a. In the simulation model describing the electron beam, the PXR-target (crystal), a possible filter, and a view screen (scintillator), the screen was assumed to consist of a matrix of 10x10 µm pixel size, located at 10 mm distance from the target center under an observation angle of 90º.

To improve the resolution in this case it is proposed to use of thin metal filters, see e.g. figure 1b. For instance a 25 µm thick Ti foil (K-absorption edge of 5.1 keV) can be used to absorb the high intense but low-energetic PXR radiation which has a broad angular distribution and therefore will spoil the spatial resolution.

**Figure 1.** Experimental scheme (a); image of the PXR beam at the view screen from a single electron (b).
The intensity of the PXR main reflection (12 0 0) downstream this filter with a photon energy of 19.5 keV amounts $10^{-6}$ ph/e see figure 2. In addition this figure shows the spatial and the spectral distribution of PXR at the scintillator from a real electron beam with a transverse size of 35×50 μm, a beam size which seems reasonable for a proposed test experiment.

![Figure 2. The image and spectrum of the PXR beam generated by a real electron beam of Gaussian distribution with $\sigma_x = 35$, $\sigma_y = 50$ μm: a) without filter; b) with filter consisting of a 25 μm thick Ti foil.](image)

Figure 3 summarizes the simulation results for the obtained PXR spot sizes (FWHM) at the view screen as function of the electron beam cross-section. As can be seen, for small electron beam spots there is a significant broadening of the transverse resolution which can however be improved by using the proposed geometry with filter.
2.2. Observation angle 30 degree

When the observation angle is 30° (figure 4), the photon energy of the first reflex (4 0 0) is 17.7 keV. Such a high photon energy allows to obtain an X-ray image without filters with sufficient spatial resolution. The intensity of the PXR reflection in this geometry amounts $10^{-3}$ ph/e$^{-}$ (figure 5), which in principle should be sufficient for beam imaging.

**Figure 3.** Dependency of the PXR spot size at the view screen (FWHM) as function of the electron beam size.

**Figure 4.** Experimental scheme (a); image of the PXR beam at the view screen from a single electron (b).
Figure 5. Spectrum and image of the PXR beam on the scintillator from real electron beam of Gaussian distribution with \( \sigma_x = 50, \sigma_y = 50 \mu m \).

Figure 6 summarizes the simulation results for the obtained PXR spot sizes (FWHM) at the view screen as function of the electron beam cross-section. In this case, both transverse beam sizes were chosen to be equal. As can be seen, for this observation geometry the resolution broadening is drastically reduced. However, it is still too large to resolve electron beam spots in the order of a few microns.

Figure 6. Dependency of the PXR spot size at the view screen (FWHM) as function of the electron beam size.

3. Conclusion

According to the simulation results it should be possible to measure transverse beam sizes in the order of \( \sigma \geq 50 \mu m \) with sufficient resolution for beam energies above 1 GeV and the observation geometry of 30 deg.

The main parameter that determines minimum resolution of this method is determined by the thickness of the crystal target that decreases with decreasing observation angle in Laue case (in Bragg case length of the path in the crystal increases), so it is necessary to carry out further optimization of the parameters in order to define a suitable geometry with an appropriate target crystal for a future test experiment.
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