METHOD OF CRYSTAL DEFLECTOR MONITORING

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Abstract

We propose to use a parametric x-ray radiation from an intense proton beam for the crystal deflector control and monitoring. The considered technique to control a radiation damage of deflector's crystal structure allows to estimate deflector bend radius and radiation heating by width of parametrical x-ray radiation line.

INTRODUCTION

There is a problem of intense beams extraction at next generation accelerators (for example, J-PARC) which can be solved using crystal deflectors. Silicon crystals are widely used for this purpose, due to a perfect crystal structure [1]. However, as it was shown at reference [2], one can considerably increase particles deflection efficiency using metal crystals with a high atomic number instead of silicon deflectors. For example, beam extraction efficiency at JINR Nuclotron for 100 mrad angle can be increased more than ten times using tungsten deflector. Besides, heavy metal crystals are more stable at radiation heating influence. But, it's a problem to manufacture tungsten deflectors with required crystalline perfection.

It's necessary to control crystal deflector parameters during intense charged particle beam extraction. For example, intensity of a J-PARC proton beam may be achieved ~ 10^{14} particles per second [3], and to date there are no researches on radiation damage of silicon deflectors radiating under such beams.

At this report the crystal deflectors quality control technique based on parametric x-ray radiation (PXR) detection is proposed [4]. For channeling relativistic protons PXR in a bent crystal was considered in the work [5] where PXR angular focusing opportunity was shown. At the report [6] we showed, that PXR spectral line width from the bent crystal depends on relative arrangement of the detector and bent crystal focus. Suggested technique gives an opportunity to control deflector crystal structure under an intense proton beam continuously (on-line). Also its possible to determine the deflector curvature radius registrating the PXR line width. The latter is especially actual for crystals, for which mirror surface manufacturing is complicated, for example, for tungsten deflector.

PROPOSED EXPERIMENTAL SCHEME

Let us choose for simulation the extraction scheme, shown at figure 1. The 50 GeV protons beam is deflected by Si crystal, which it is cut out along planes (110).

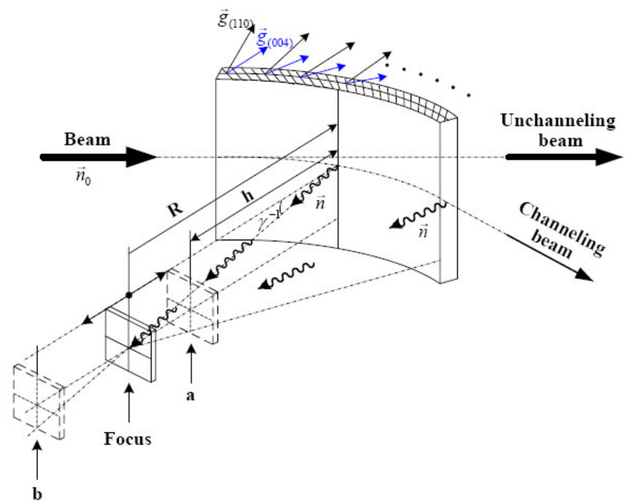

Figure 1: Experimental scheme.

Optimal bending radius of the deflector for the beam extraction is equal to 5 R_c, here R_c is the critical radius of channeling. For silicon crystal (110) $R_c \approx E/6$ [cm], E – proton energy in GeV [1]. So almost optimal deflector bending radius of crystal is about R = 40 cm. Let us choose R = 50 cm and h = 40 cm detector distance (see Fig.1). For deflection at angle $\alpha = 0.1$ rad deflector length had to be L = 5 cm. For slight angular divergence beam extraction efficiency is about 20%. Let us choose deflector height and width to be equal to 1 cm and 0.1 cm, correspondingly.

X-ray emission is measured by semiconductor detector with sensitive area ~ 10 mm^2 and resolution ~ 100 eV.

CALCULATION PROCEDURE

Protons crosses a set of crystallographic planes moving along the bent planes (110) in channeling regime, so PXR generates in Bragg directions relatively to these planes.

Many PXR experimental researches have shown that kinematic model is valid for description of observable PXR properties generated in thin straight crystals. Thus, at first approximation it's possible to use this model for calculation of PXR yield from the bent crystal. Let us consider a bent crystal as a set of *n* the straight samples tilted at angle *α/n* relative to each other. Then PXR yield from all crystal can be presented as superposition of separate contributions from each sample using the following formula:

$$\frac{dN}{dLd\Omega} = \sum_{i=1}^{n} \left(\frac{dN}{dld\Omega} \right)_i , \qquad (1)$$

where L – bent crystal length, $l = L/n$ – thickness of sample, $(dN/dld\Omega)_i$ is determined by following formula [7]:

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$$\left(\frac{dN}{dld\Omega}\right)_i = \frac{Z^2\alpha}{2\pi\eta}\sum_g \frac{(\omega/c)^3|\chi_g|^2}{\beta(1-\sqrt{\varepsilon}\boldsymbol{\beta}\cdot\mathbf{n})}\times$$
$$\times\sum_\alpha\left[\frac{(\sqrt{\varepsilon}(\omega/c)\boldsymbol{\beta}-\mathbf{g})\cdot\mathbf{e}_{\mathbf{k}\alpha}}{\mathbf{k}_g^2-(\omega/c)^2}\right]^2, \qquad (2)$$

where Z – charge of an incident particle, α – fine structure constant, **g** − reciprocal lattice vector, **n** – unit vector at direction of PXR photon, $\boldsymbol{\beta}$ – normalized electron speed vector, $\beta = v/c$, c – velocity of the light, ε – permittivity of the crystal matter, $\omega = \mathbf{g}\,\boldsymbol{\beta}/(1 - \sqrt{\varepsilon}\,\boldsymbol{\beta}\,\mathbf{n})$ – photon energy, ω_p – crystal matter plasmon energy, γ – Lorentz-factor, $\mathbf{e}_{\mathbf{k}\alpha}$ – unit vector of polarization, $\mathbf{k}_g = \mathbf{k} + \mathbf{g}$.

Permittivity in x-ray range can be approximated by the expression:

$$\varepsilon = 1 + \chi = 1 - (\omega_p/\omega)^2, \quad |\chi| \approx (\omega_p/\omega)^2 << 1. \qquad (3)$$

It's wellknown, that for diffraction at a crystal as in any periodic structure function χ from eqs. (3) can be expanded in a Fourier series on reciprocal lattice vector, and expansion coefficients $\chi_{\mathbf{g}}$ may be written in the following manner:

$$|\chi_g|^2 = |S(\mathbf{g})|^2 \exp[-2W]\left(-\frac{\omega_p^2}{\omega^2}\frac{F(\mathbf{g})}{z_c}\right)^2, \qquad (4)$$

where $|S(\mathbf{g})|^2$ – structure factor, $\exp[-2W]$ – Debye-Waller factor, $F(\mathbf{g})$ – Fourier component of electron density distribution of atom, z_c – number of electrons in a crystal elementary cell.

SIMULATION RESULTS

Spectral-angular distribution of radiation generated by the proton crossing (100) planes tilted by 45˚ relative to deflecting silicon crystal planes (110) is calculated using the developed approach. PXR photons are concentrated at the optical focus of bent crystal surface. One may compare figure 2a (PXR (100) reflection distribution from straight crystal with length 5 cm) and figure 2b (PXR (100) reflection distribution from bent crystal with the same length). The focusing effect allows considerably reduce a time of measurements due to statistics increased. Spectral line width of PXR has the minimum if X-ray detector was placed in the focus. PXR line width of depends on crystal curvatures [6]. For the chosen geometry PXR line is equal to 6.5 keV. This value was calculated with taking into account energy resolution of the detector (~ 100 eV). PXR angular density *dN/dΩ* in focus pointhas been equal to 0.25 photon/sr/p_d for channeling protons. For particles passing through a crystal without a deflection (just along the initial direction) the focusing also is observed but it is caused not by changing of observation angle as in channeling fraction beam the case but by changing of Bragg angle, and the PXR angular density in focus was equal to 0.06 photon/sr/p_u. For other set of planes the focussing effect - the reduction of PXR distribution image sizes of the fixed space area is observed also.

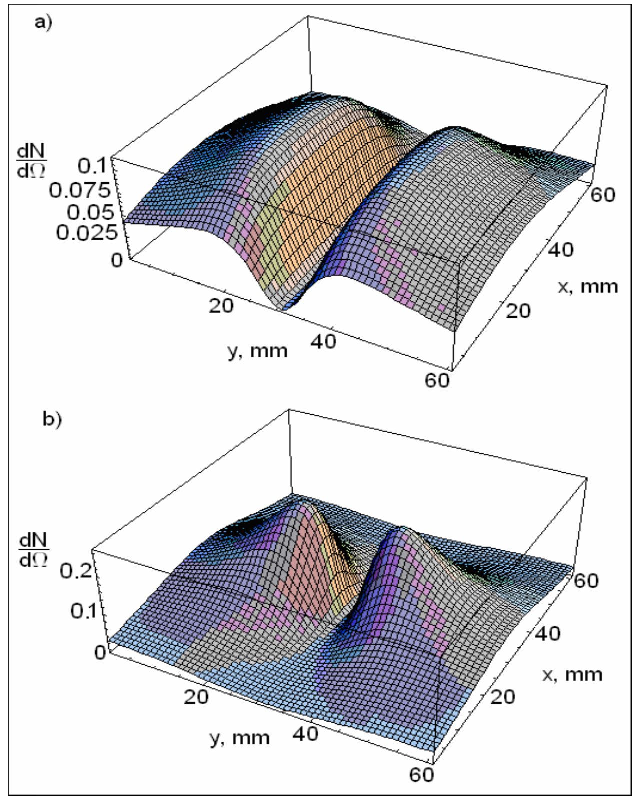

Figure 2: PXR angular distribution of (100): a) from straight crystal with length 5 cm; b) from bent crystal with length 5 cm and bending radius R = 50 cm. Distance to the detector plane is 50 cm.

During simulation the approximation that 20 % of particles were deflected at the angle 0.1 rad by silicon deflector with length 5 cm was used. At this stage we consider that dechanneling beam fraction i.e. 80 % particles passes through the crystal along the initial direction. Characteristics of PXR spectral line full width at half maximum and peak intensity with taking into account contributions from two beam fractions (see fig. 3) were calculated for the arrangement of the detector at position *a* (see fig. 1). This scheme was chosen because for it the proposed technique is more sensitive to changes of bending radius for *R* > 40 cm. PXRintensities dependences were calculated at temperature range from 0 ^{o}C up to 1300 ^{o}C (1410 ^{o}C - silicon fusion temperature; 660 ^{o}C – Debye temperature).

The deflector crystal structure can be damaged under an intense beam during a long exposition. The perfect ness of deflector crystal structure control may be carried out observing the PXR line. Besides, according to simulation results (fig. 3) it is possible to estimate the temperature of deflector by registrating PXR line FWHM and intensity.

If it is necessary to have more exact information about deflector bending radius one can carry out a few additional measurements of PXR lines for various

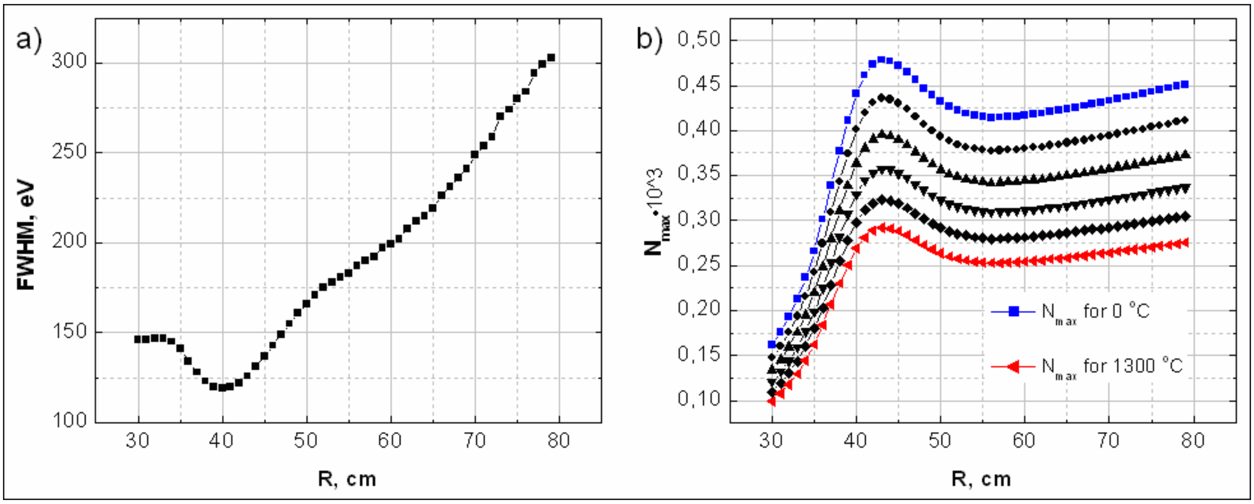

Figure 3: Simulated dependences on deflector radius: a) FWHM of PXR; b) PXR line intensity.

positions of the detector on an optical axis of deflector (see fig. 4).

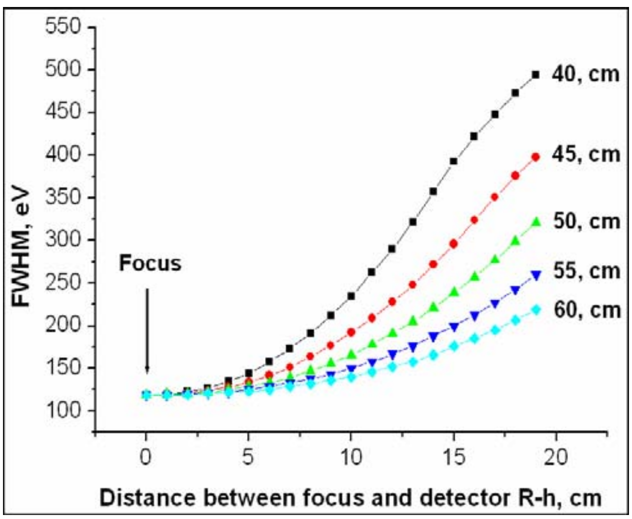

Figure 4: Dependence of PXR line width on detector positions for different deflector bending radius.

SUMMARY

PXR spectral-angular distribution simulation method for bent crystals based on the kinematic model of PXR is offered. Simulation results show PXR angular focusing from the bent crystals and presence of PXR spectral line width dependence mean the deflector bend and position.

We propose to use PXR as a diagnostics tool for on-line monitoring of a quality and parameters of crystal deflector.

The PXR spectral line width allows to estimate a curvature radius of deflector.

Degradation of line intensity may be used for determination of deflector temperature and/or radiation damage.

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