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Focusing of high energy particles with the help of bent single crystal

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ABSTRACT

In this report, the continuation of studies (Afonin et al., 2003, 2012; Scandale et al., 2014) of focusing properties of bent single crystals is presented. Recently, the possibility of transforming a parallel beam into the point-like one has been demonstrated theoretically and experimentally (Scandale et al., 2014). Here we study an inverse problem of conversion of a point-like beam into the parallel one. It is shown that, by exploiting such a capability, the significantly more intensive secondary particle beams could be generated compared to usage of other conventional method.

1. Introduction

The capabilities of bent crystals for focusing positive particle beams have been demonstrated the first time in the experiment of Ref. [4]. The suggested there explanations of the observed effects were based on geometrical relations for bent cylindrical surfaces.

Since then, the focusing with bent single crystals have been studied in a number of papers including the most recent ones [1–3]. The comprehensive measurements with many detailed results have been presented in publication [3] along with the simple mathematical description of focusing properties. The similar mathematics for these phenomena can also be found in Ref. [1].

This paper represents the continuation of studies [1–3] of the focusing properties of bent single crystals. In the paper [3], the case of focusing a parallel beam into the point-like one has been considered. Here we study an inverse problem of converting a point-like beam into the parallel one with the help of bent single crystal. The applications of such type of focusing for extraction of secondary beams from accelerators are discussed.

2. Mathematical description

Fig. 1 illustrates the two cases of focusing of high energy particle beam. The first case (Fig.1a corresponds to focusing of a practically parallel beam into a point-like beam. This method of focusing was presented in detail in the paper [3]. In this paper was shown that the envelope of deflected beam (by a bent single crystal) is described by the following equation:

$$\sigma_x(l) = \langle x^2\rangle - \bar{x}^2 + (\langle\varphi^2\rangle - \bar{\varphi}^2 + \langle\theta^2\rangle - \bar{\theta}^2)l^2 + 2(\langle x\varphi\rangle - \bar{x}\bar{\varphi})l, \quad (1)$$

where $\sigma_x(l)$ is the mean square size of beam on a distance equal to l from the crystal, $\langle x^2\rangle$ and $\bar{x}$ are the mean square and mean size of beam at distance $l = 0$, $\langle\varphi^2\rangle$ and $\bar{\varphi}$ are the mean square and mean angle of beam deflection, $\langle\theta^2\rangle$ and $\bar{\theta}$ are the mean square and mean angle of beam particles due to oscillatory motion at channeling regime.

Fig. 1b illustrates the inverse case of focusing, when the point-like beam from point O' (on a distance equal to focal length from the crystal) is transformed into practically parallel beam. We can obtain the following equation:

$$\sigma_x(t) = \sigma_x(l_0) + (\langle\varphi^2\rangle - \bar{\varphi}^2 + \langle\theta^2\rangle - \bar{\theta}^2)t^2 - 2[(\langle x\varphi\rangle - \bar{x}\bar{\varphi}) + (\langle\varphi^2\rangle - \bar{\varphi}^2 + \langle\theta^2\rangle - \bar{\theta}^2)l_0]t \quad (2)$$

Here l_0 is some fixed point at the distance $l = l_0$ from the crystal. Then variable $t = l_0 - l > 0$. The distance t is equal to NK straight line and $l_0 = MN$ in Fig. 1a.

Let us consider the case when $l_0 = l_f$, where

$$l_f = -\frac{\langle x\varphi\rangle - \bar{x}\bar{\varphi}}{\langle\varphi^2\rangle - \bar{\varphi}^2 + \langle\theta^2\rangle - \bar{\theta}^2} \quad (3)$$

is the focal length. Then

$$\sigma_x(l_f) = \langle x^2\rangle - \bar{x}^2 - \frac{(\langle x\varphi\rangle - \bar{x}\bar{\varphi})^2}{\langle\varphi^2\rangle - \bar{\varphi}^2 + \langle\theta^2\rangle - \bar{\theta}^2} \quad (4)$$

$$\sigma_x(t) = \sigma_x(l_f) + (\langle\varphi^2\rangle - \bar{\varphi}^2 + \langle\theta^2\rangle - \bar{\theta}^2)t^2 \quad (5)$$

Let us assume that $\varphi(x) = kx/R_0$ and the particle density distribution function is $\rho(x) = 1/d$, where d is the transversal size of the crystal deflector. Then $\langle x^2\rangle - \bar{x}^2 = d^2/12$, $\langle\varphi^2\rangle - \bar{\varphi}^2 = k^2d^2/(12R_0^2)$,

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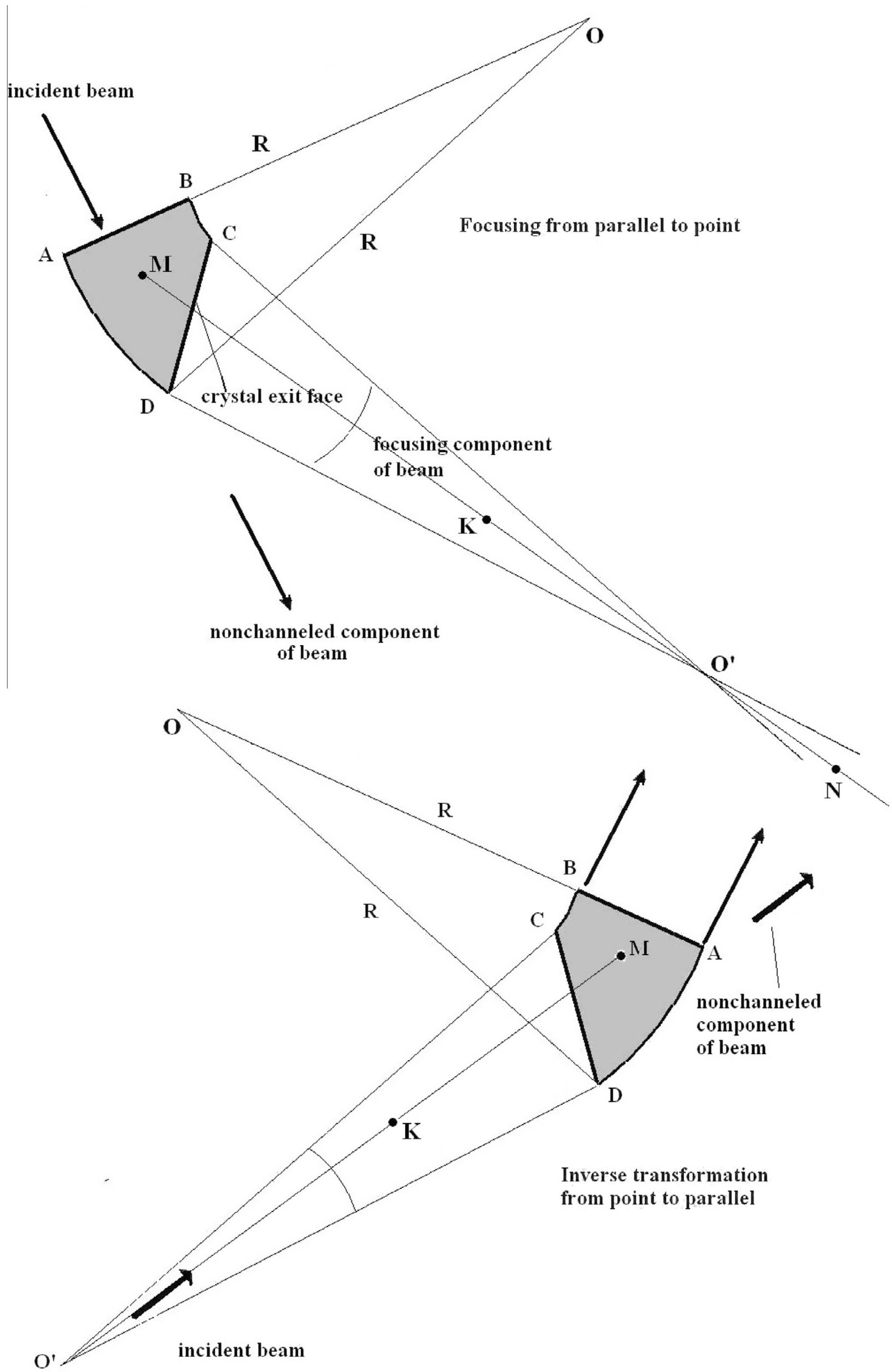

Fig. 1. (a) Focusing of parallel beam into point-like one: $l_0 = NM$, $l = KM$ and $t = l_0 - l = NK$; (b) the inverse focusing point-like beam into parallel: $O'K = l_f$, $t = O'K$.

$\langle x\varphi\rangle - \overline{x}\,\overline{\varphi} = kd^2/(12R_0)$. Note here we consider the linear dependence between the x and z coordinates ($z = kx$).

Then

$$l_f = -\frac{R_0}{k}\frac{1}{1+12\delta^2R_0^2/(k^2d^2)} \approx -\frac{R_0}{k}(1-12\delta^2R_0^2/(k^2d^2)) \approx -\frac{R_0}{k} \qquad (6)$$

$$\sigma_x(l_f) = \frac{\delta^2R_0^2/k^2}{1+12\delta^2R_0^2/(k^2d^2)} \approx \delta^2R_0^2/k^2 \qquad (7)$$

where we introduced $\delta^2 = \langle\theta^2\rangle - \overline{\theta}^2$. We estimate $\delta^2 \approx \theta_c^2/3$ (see Ref. [3]) ($\overline{\theta} = 0$) where θ_c is critical channeling angle.