Nuclear Instruments and Methods in Physics Research B 402 (2017) 296–299

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Splitting of a high-energy positively-charged particle beam with a bent crystal

L. Bandiera [a,b,*], I.V. Kirillin [c], E. Bagli [a,b], A. Berra [e,f], D. De Salvador [g,h], V. Guidi [a,b], D. Lietti [e], A. Mazzolari [a,b], M. Prest [e,f], N.F. Shul'ga [c,d], A. Sytov [a,b], E. Vallazza [i]

[a] INFN Sezione di Ferrara, Via Saragat 1, 44122 Ferrara, Italy
[b] Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara, Via Saragat 1, 44122 Ferrara, Italy
[c] Akhiezer Institute for Theoretical Physics, National Science Center "Kharkov Institute of Physics and Technology", Akademicheskaya Str., 1, 61108 Kharkov, Ukraine
[d] V.N. Karazin Kharkov National University, Svobody Sq. 4, 61022 Kharkov, Ukraine
[e] INFN Sezione di Milano Bicocca, Piazza della Scienza 3, 20126 Milan, Italy
[f] Università dell'Insubria, via Valleggio 11, 22100 Como, Italy
[g] INFN Laboratori Nazionali di Legnaro, Viale dell'Universitá 2, 35020 Legnaro, Italy
[h] Dipartimento di Fisica, Universitá di Padova, Via Marzolo 8, 35131 Padua, Italy
[i] INFN Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy

A R T I C L E I N F O

Article history:
Received 9 December 2016
Received in revised form 16 March 2017
Accepted 21 March 2017
Available online 28 March 2017

Keywords:
Beam splitting
Bent crystal
Channeling

A B S T R A C T

The possibility of high-energy positively-charged particle beam splitting by means of a short bent axially oriented silicon crystal was recently reported in an experiment carried out at CERN SPS H8 extracted line with a 400 GeV/c proton beam. Here, we investigate more deeply such a possibility focusing our attention on the efficiency of beam splitting and its modulation for different crystal-to-beam orientations. New experimental results confirm the possibility of modulating the 400 GeV/c proton beam intensity in different planar channels by adjusting the orientation of the crystal. Furthermore, an analysis of the beam splitting efficiency vs. the curvature of the crystal was carried out through simulation, highlighting that there exists a bending radius for which the efficiency is maximal.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

Since in 1976, when Tsyganov proposed [1,2] to use a bent crystal for particle beam deflection, such a possibility found a lot of applications in accelerator physics. First studies on beam deflection by a bent crystal were connected to planar orientation of the crystal [1–3]. Then in 1991 there was a proposition to use axially-aligned bent crystal [4]. The advantage of axial orientation is the strongest potential than for planar case and the possibility to deflect above-barrier particles. The axial case was theoretically investigated in [5] and then experimentally proved in [6–9].

Recently, it was observed that under some crystal-to-beam orientation is possible to split the beam of high-energy positively-charged particles into two good-collimated parts [10]. This happens if the crystal is oriented along one of its main crystallographic axes towards the beam direction and if this axis lies in the bending plane of the crystal. In this case for some radii of curvature particles relax from axial confinement to planar channeling [11] in different skew planes during their motion in the crystal and thus becoming well separated at the crystal exit. This possibility can be exploited to realize a multi-beam extraction point layout at just one extraction point of a circular accelerator. Moreover, the intensity of particles in each channel can be adjusted by tuning the beam direction with respect to the crystal axis. In this paper we investigated such possibility of beam intensity adjustment and carried out the analysis of beam splitting efficiency vs. the radius of curvature of the crystal.

2. Capture to skew planar channels

Let us consider the motion of a relativistic charged particle in a thin bent crystal near one of the main crystallographic axes. Without loss of generality, let it be the $\langle 111 \rangle$ axis. Term "thin" here means that the bending radius of the crystal is much higher than the thickness of the crystal. Bent $\langle 111 \rangle$ axis is assumed to lie in the bending plane. For our consideration we choose two Cartesian coordinate systems. One is laboratory frame (x, y, z) in which y axis is orthogonal to the bending plane, z axis lies in the bending plane

* Corresponding author at: INFN Sezione di Ferrara, Via Saragat 1, 44122 Ferrara, Italy.
E-mail address: bandiera@fe.infn.it (L. Bandiera).

http://dx.doi.org/10.1016/j.nimb.2017.03.109
0168-583X/© 2017 Elsevier B.V. All rights reserved.

and its direction coincides with the initial direction of $\langle 111\rangle$ axis, and x axis is orthogonal to y and z. The second coordinate system (x', y', z') is co-moving. This system moves with respect to the laboratory frame with the speed of the particle in such a way that the center of co-moving frame lies on the bent $\langle 111\rangle$ crystal axis; y' axis is parallel to y axis, x' axis coincides with vector of curvature and z' axis coincides with a current direction of the bent $\langle 111\rangle$ axis. In such non-inertial system the equations of particle motion in a thin bent crystal can be written as [4,12]

$$\frac{d^2x'}{dt^2} = -\frac{c^2}{E}\frac{\partial U(x',y')}{\partial x'} - \frac{c^2}{R}$$
$$\frac{d^2y'}{dt^2} = -\frac{c^2}{E}\frac{\partial U(x',y')}{\partial y'}$$
$$\frac{d^2z'}{dt^2} = 0, \qquad (1)$$

where E is the particle energy, R is the radius of curvature of the crystal, and $U(x', y')$ is continuous potential [11] of unbent crystal atomic strings, that are parallel to z-axis. The last term in the first equation of (1) corresponds to the centrifugal force $-E/R$ experienced by the particle in the co-moving frame. The smaller the radius of curvature, the higher the centrifugal force, thus increasing the probability of particle escape from axial confinement to planar channeling in skew planes [10]. However, capture in a skew planar channel is possible only if the absolute value of the projection of the centrifugal force to the axis ζ, that is orthogonal to the skew plane, is less than the maximum value of the derivative of particle potential energy in the planar channel: $\frac{E}{R}\sin\left|\varphi_{pl}\right| < \max\left(\left|\frac{\partial U_{pl}(\zeta)}{\partial \zeta}\right|\right)$, where φ_{pl} is the angle between the skew plane and the bending plane. If this condition is not fulfilled, the particle is above-barrier with respect to the chosen planar channel. Thus, for each skew planar channels there exists some critical radius of curvature that can be written as follow:

$$R_{cr} = \frac{E\sin\left|\varphi_{pl}\right|}{\max\left(\left|\frac{\partial U_{pl}(\zeta)}{\partial \zeta}\right|\right)}. \qquad (2)$$

If the radius of curvature is smaller than R_{cr}, planar channeling in the correspondent skew planar channel is forbidden.

For our theoretical investigation, we selected 400 GeV/c protons and the same crystal orientation as in [10], with bending plane $(\bar{1}\bar{1}2)$ and, thereby, y axis in the $(1\bar{1}0)$ plane (see Fig. 1). The geometrical characteristics of the crystal are also the same; thickness $L = 2$ mm and radius of curvature $R = 6.9$ m. In such a case, the two strongest skew planar channels are $(0\bar{1}1)$ and $(\bar{1}01)$ (shown in Fig. 1 by red and magenta points, respectively) and for them $\left|\varphi_{pl}\right| = \pi/6$. For this channels from Eq. (2) we obtain $R_{cr} \approx 35$ cm, thus $R \gg R_{cr}$.

In [10] it was shown that if protons enter into the crystal parallel to the z axis, i.e., parallel to the $\langle 111\rangle$ axes, almost half of the beam is deflected at the crystal exit due to capture in planar channeling by the $(0\bar{1}1)$ skew plane and another half is deflected because of planar channeling in the $(\bar{1}01)$ skew plane. So, with respect to the bending plane, the angular distribution of protons was symmetric. However, if the angle between the initial momentum of protons and z axis $\vec{\psi}_{in} = (\theta_{x,in}, \theta_{y,in})$ is nonzero, one could expect an asymmetrical distribution. Even if two skew planar channels are located symmetrically with respect to the bending plane (as $(0\bar{1}1)$ and $(\bar{1}01)$ planes in our case) a small misalignment with respect to the bent axis in the initial crystal-to-beam orientation may lead to the asymmetry in the number of particles, captured by the planar channels. Furthermore, also the number of particles captured by skew planar channels should depend from $\vec{\psi}_{in}$.

By means of numerical simulation we carried out the analysis of the dependence of protons capture to $(0\bar{1}1)$ and $(\bar{1}01)$ skew planar channels from the angle $\vec{\psi}_{in}$. The code [13] solves the equation of motion in the field of continuous potential of atomic strings through numerical integration and also takes into account the contribution of incoherent scattering with atomic nuclei and electrons. Thus, the code gives an opportunity to consider axial and planar channeling, stochastic deflection and above-barrier motion within a single model. The angular divergence of the initial beam was set to zero. The results of simulation are shown in Fig. 2. Colors correspond to the percentage of the number of particles, captured by skew planar channels $(0\bar{1}1)$ and $(\bar{1}01)$ ($N_{(0\bar{1}1)}$ and $N_{(\bar{1}01)}$, respectively), to the total number of particles in the initial beam N. With "captured by skew planar channels", we means that only protons for which, after crossing the crystal, the angle between the skew plane and projection of their momentum to (x, y) plane is less than the critical angle for planar channeling θ_c (≈ 10 µrad for (110) skew planes) are selected. From the definition of θ_c, it is clear that

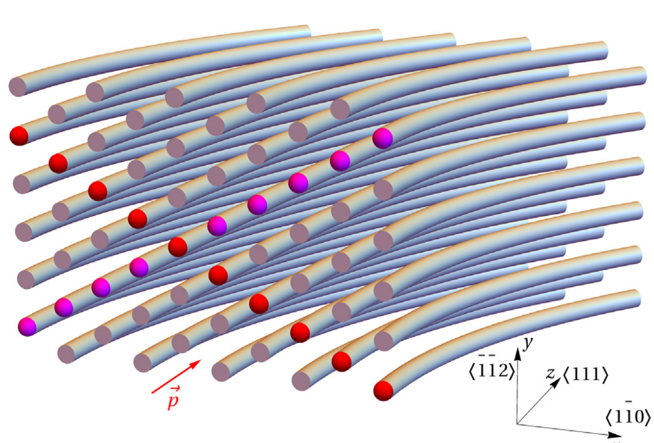

Fig. 1. Orientation of a bent Si crystal $\langle 111\rangle$ axes with respect to the impinging charged particles; red and magenta points highlight the two main skew $(0\bar{1}1)$ and $(\bar{1}01)$ planes.

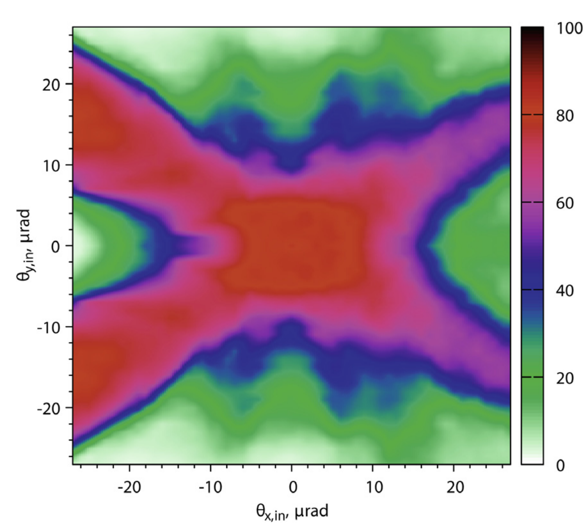

Fig. 2. Simulated efficiency of 400 GeV/c proton beam splitting, i.e., capture by skew planes, for a 2 mm Si crystal with $R = 6.9$ m vs. angle $\vec{\psi}_{in} = (\theta_{x,in}, \theta_{y,in})$ between $\langle 111\rangle$ crystallographic axis and initial direction of motion of the beam (colors show the percentage of protons captured in $(0\bar{1}1)$ and $(\bar{1}01)$ planar channels to the total number of protons in the beam).

Download English Version:

https://daneshyari.com/en/article/5467811

Download Persian Version:

https://daneshyari.com/article/5467811

Daneshyari.com