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High energy neutrino beam generation based on crystal optics

Yu.A. Chesnokov, V.A. Maisheev [*]

NRC Kurchatov Institute - IHEP, 142281, Protvino, Russia

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ABSTRACT

The problem of creation of high energy neutrino beams on the basis of modern and future circular proton accelerators with the help of traditional technology seems to be expensive and difficult. Because of this, we propose the solution of this problem based on the usage of focusing bent single crystals. In the paper we demonstrate the possibilities of acceptance and focusing of a pion beam with the help of a crystal optical lens system. As an illustration of these features the calculated neutrino fluxes for energy of circulating proton beam equal to 6.5 TeV are presented.

1. Introduction

The development of experimental physics of elementary particles is accompanied by the creation of accelerators with ever higher energy. At present, LHC is the accelerator with the highest proton energy. The previous high energy accelerators are the SPS (CERN) and Tevatron (Fermilab). It is well known that such accelerators can be used in two modes. The first mode is a collider mode when two independent accelerated beams (moving in the opposite directions) collide inside the vacuum chamber at special intersection points. The apparatus standing around this points allow one to obtain information about proton–proton (or nuclear–nuclear) interactions. The second mode is the production of secondary beams (such as beams of pions, muons, electrons, neutrinos and others). Experiments using such beams (fix target experiments) also make it possible to obtain important information about interactions of various high-energy particles.

Until now, the LHC operates only in collider mode. However there is the project, in which the possibilities of the creation of secondary hadron beams for some experimental program [1,2] are considered. In the project the authors assume to use bent single crystals for extraction of proton beam from LHC.

Besides, in the papers [3,4] another possibility to obtain secondary beams was considered. It is based on the idea to produce secondary particles on the target located inside the vacuum chamber of the accelerator. These particles are extracted from the accelerator with the help of special focusing crystals. The focusing crystals can accept secondary particles in a wide angle range, and, hence, they can extract the secondary beam from accelerator. Additionally, the focusing crystals can focus a secondary beam on a target of experiment. In Ref. [4] for conditions of LHC the example of beam line of positive secondary particles was presented. The authors estimate the total length of this beam line about 250 m.

Neutrino interactions is one of central directions in study of particle physics. In particular, these processes are investigated on proton circular accelerators with the use of specially formed neutrino beams. The neutrino beams are the result of decays as $\pi^{\pm} \rightarrow \mu^{\pm} + \nu(\hat{\nu})$. The special devices are used for increasing flux of a neutrino beam. These devises (magnetic horns) focus parent particles (π and K-mesons) into beam close to parallel one. Thus generation of the neutrino beam requires the several stages: (1) to create the pion beam with the help of the proton beam interacting with a target; (b) to accept effectively the pion beam into a lens device; (c) to transform the pion beam into approximately a parallel beam; (d) to allow the pion beam to decay in reaction $\pi^{+} \rightarrow \mu + \nu$; (e) to deflect the background particles from a direction of neutrino beam propagation. The solution of such problems in the range of TeV energies of accelerated protons on the basis of traditional technology seems to be expensive and complex.

Because of this, we propose the solution of the problem based on the usage of focusing bent single crystals. In the paper we demonstrate the possibility creation of high energy neutrino beam on the basis crystal optics elements.

This paper is devoted to a study of possibilities of creation neutrino beams on circular proton supercolliders. For this aim we propose to use special focusing bent single crystals (see [5] and literature therein). The main purpose of our study is the demonstration of reality of obtaining intensive enough neutrino beams with a wide energy spectrum on the basis of focusing bent single crystals.

The paper is organized as follows. First, we demonstrate progress in manufacture of the focusing crystals and discuss the method which allow one to accept valuable part of secondary particles and to transform this flux into a practically parallel beam. In the next section we present calculated energy spectra of pions which can be obtained as result interaction of 6.5 TeV proton beam with the target. After this we find

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[*] Corresponding author.
E-mail address: maisheev@ihep.ru (V.A. Maisheev).

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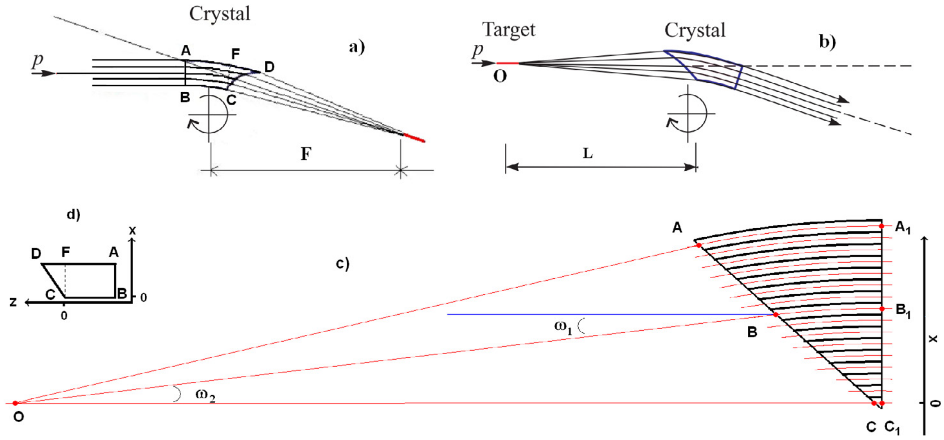

Fig. 1. Focusing bent crystals: (a) focusing of parallel beam into point, (b) focusing of point-like beam into parallel, (c) the principle of the operation of a focusing crystal (for the case (b)), (d) focusing crystal before installation in the holder. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the neutrino fluxes emitted within several given angles. Then after short discussion the conclusion follows.

2. Focusing crystals as a tool for obtaining parallel pion beam

The first measurements of the beam focusing effect were performed in the 1990s [6,7]. Since then the focusing devices have been significantly improved [5]. Fig. 1 illustrates the operation principle of such devices. The focusing crystal is represented by a sum of rectangle ABCF and triangle FCD (see Fig. 1a). Positively charged particles entering the bent crystal in channeling regime are deflected through the same angle over the distance BC (AF). For a sufficiently large deflection angle, the channeled and nonchanneled particles (background) are spatially separated. The triangular part of the crystal deflects particles with different transverse coordinate x according to a linear relationship between the angle and coordinate. Therefore, the particle trajectories converge at some (focal) point. The results of recent study of strip focusing crystals one can find in the paper [5].

Fig. 1b illustrates the inverse case of focusing, when the point-like beam from point O (on a distance L equal to focal length L_f from the crystal $L \approx L_f$) is transformed into practically a parallel beam. In this case the beam with a small size (in bending plane) and with a valuable angle divergence may be transformed into parallel one. The paper [4] contains the theoretical description of the inverse focusing and Ref. [8] is devoted to the experimental observation of this focusing mode.

Taking into account the importance of inverse focusing for our study we will consider more detail this case (see Fig. 1c). In Fig. 1c, for clarity, only the triangular part of the focusing crystal is shown. Here thick (black) circular arcs represent the planar crystallographic channels and the thin (red) arcs correspond to centers of these channels. It is easy to see that these arcs are the projections of crystallographic planes on the plane of bending. The thin (red) lines (defined by A_1, B_1, C_1 letters) are perpendicular to the surface of crystal. The straight lines as AO, BO, CO are the tangents to corresponding arcs located on a surface of the linear cut. There are two angles shown in Fig. 1c. They are ω_1 and ω_2. Obviously, that $\omega_1 = |BB_1|/R$ and $\omega_2 = X/L$, where $|BB_1|$ is the length of arc BB_1, R is the bending radius of the crystal and L is the distance between crystal and O-point. Fig. 1d illustrates the crystal in Cartesian system of coordinates before its bending. In this system for the line CD the transverse coordinate x is connected with the longitudinal coordinate z by the equation $z = kx$, where k is a constant coefficient. It is obvious that $\omega_1 = \omega_2$. From here we found that $L = R/k$ and we see that the L value is independent of x and z coordinates. The distance L is practically equal to the focal length L_f of a bent single crystal (see Ref. [5]):

$$L = L_f \approx R/k \tag{1}$$

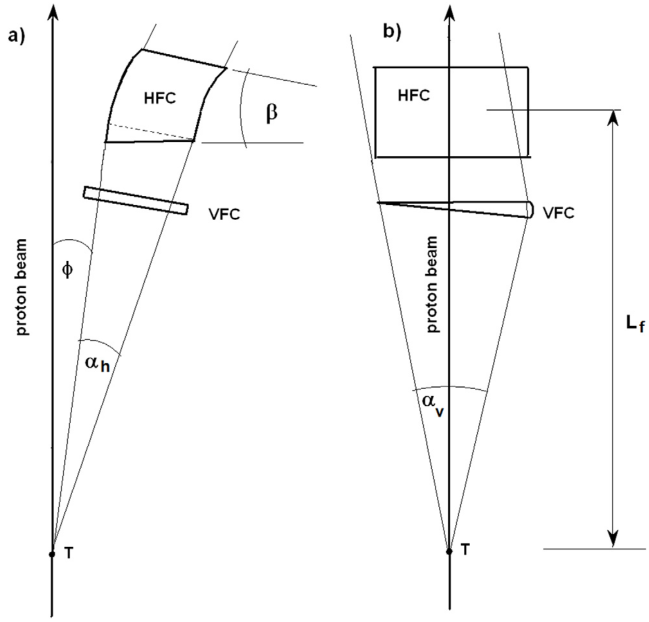

Fig. 2. Scheme of generation and formation of a parallel beam of pions: HFC and VFC are horizontal and vertical bent focusing single crystals, correspondingly, α_h and α_v are horizontal and vertical angles of acceptance of pions, respectively, β is the bending angle, ϕ is angle between the proton beam and the edge of the crystal, L_f is the focal length of the crystals T is the target. (a) top and (b) side view.

We see also that any positively charged particle emanating from a point O within the maximal and minimal angles $\omega(x)$ ($\omega_{2,max} = d/L$, $\omega_{2,min} = 0$, d is the transverse thickness of crystal) moves along the straight line and enter in the crystal practically under zero angle relative to crystallographic planes. It means that the positive particle may be accepted in a channeling regime. Thus, the accepted channeled particles are formed into a parallel beam. This process was studied in details in the paper [4]. From this study follows that the total efficiency of transformation of the beam into parallel is equal to the product $w_T = w_o w_c$, where w_o is the geometrical efficiency (probability) for a particle emitted from point O to be on the surface of the cut in limits of a critical angle of channeling θ_c relative to the direction of crystallographic planes and w_c is the probability (the efficiency) for a particle moving under angle less than θ_c relative to crystallographic planes to be captured in channeling and to conserve this statement up to exit from the body of bent crystal. According to the paper [4] the efficiency w_o is maximal when the distance from the point O to crystal is equal to the focal length