ENERGY LOSS DISTRIBUTIONS OF 7 TeV PROTONS CHANNELED IN A BENT SILICON CRYSTALS

by

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The energy loss distributions of relativistic protons axially channeled through the bent <100> Si crystals, with the constant curvature radius, R = 50 m, are studied here. The proton energy is 7 TeV and the thickness of the crystal is varied from 1 mm to 5 mm, which corresponds to the reduced crystal thickness, Λ, from 2.1 to 10.6, respectively. The proton energy was chosen in accordance with the large hadron collider project, at the European Organization for Nuclear Research, in Geneva, Switzerland. The energy loss distributions of the channeled protons were generated by the computer simulation method using the numerical solution of the proton equations of motion in the transverse plane. Dispersion of the proton scattering angle caused by its collisions with the crystal's electrons was taken into account.

Key words: relativistic channeling, bent crystal, energy loss distribution

INTRODUCTION

It is well known that the energy loss of an ion during its passage through the crystal depends on its orientation with respect to the crystallographic axis or planes [1]. When high energy charged ion is channeled, their motion is mostly restricted in the region with lower electron density, and, accordingly, its energy loss is mostly determined from the distant collisions with the crystal's electrons. In the case of random orientation of the ion beam with respect to crystal, the ion energy loss is determined from both close and distant collisions with the crystal's electrons [2]. Therefore, the random (average) ion energy loss is larger than the channeling one.

The channeling effects in the straight and bent crystals have been studied in details theoretically [2], experimentally [3, 4] and using methods of the computer simulations [5, 6]. It has been also shown that the reduced crystal thickness Λ can classify the angular distributions of axially channeled ions in the straight or bent crystals [7-9]. The reduced crystal thickness is defined by the expression: $\Lambda \quad f L \nu$, where f is the frequency of transverse motion of ion moving close to the atomic strings, L – the crystal thickness, and ν – the ion velocity. Frequency f is determined from the Taylor expansion of the continuum potential of the crystal in the vicinity of the channel axis [9, 10]. The values of $\Lambda = 0, 0.5, 1, \ldots$ correspond to the beginnings of the angular distribution cycles [10].

In this work, the energy loss distributions of relativistic protons channeled in the bent <100> Si crystal, with the constant curvature radius, R = 50 m, are studied. The proton energy is 7 TeV and the thickness of the crystal is varied from 1 to 5 mm, which corresponds to the reduced crystal thicknesses from 2.1 to 10.6, respectively. The proton energy was chosen in accordance with the Large Hadron Collider project, at the European Organization for Nuclear Research, in Geneva, Switzerland.

THEORY

The system under consideration is an ion which enters a bent silicon crystal at small angles with respect to some of the main crystallographic axis. As a result of the ion-crystal interaction, which consists of ion-atomic strings interactions, the centrifugal force due to the crystal curvature acting on the ion, and the ion interaction with the crystal's electrons, the (average) transversal kinetic energy of ion is increasing as the ion passes through the crystal, meaning that (average) angle of ion velocity vector with respect to the crystal axis is increasing. When this angle is larger than the critical an-

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gle for channeling [1] $\psi_c = (4Z_1Z_2e^2/p\upsilon d)^{1/2}$, where Z_1 and Z_2 are the atomic numbers of ion and atoms of the crystal, respectively, e is the elementary charge, p – the ion (relativistic) impulse and d – the distance between the atoms in the atomic string; the ion is treated as being dechanneled.

In the calculation of the ion energy loss, we assume that the continuum interaction potential of the ion and the i-th atomic string of the crystal is given by the Lindhard's expression [1]

$$U_i \quad \frac{Z_1 Z_2 e^2}{d} \ln \frac{Ca_s^2}{p_i^2} \quad 1 \qquad (1)$$

where p_i is the distance between the ion and the i-th atomic string, $a_s = [9 \quad /128]$ ($Z \quad Z \quad ^{-} \quad a$ – the screening radius, a_0 – the Bohr radius, and C – the screening constant. The thermal vibrations of the crystal atoms are taken into account via expression [10]

$$U_i^{th}(x, y) \quad U_i(x, y) \quad \frac{\sigma_{th}^2}{2} \Delta U_i(x, y) \qquad (2)$$

where U_i is the continuum potential of the i-th atomic string with the thermal vibrations of the atoms neglected, $\partial_{xx} + \partial_{yy}$, x and y are the transverse components of the ion position, and σ_{th} is the one-dimensional thermal vibration amplitude of crystal atoms. The continuum potential of the crystal, U^{th}, is the sum of the continuum potentials of the atomic strings.

For the relativistic ion stopping power we use expression [11, 12]

$$\frac{dE}{dz} \quad \frac{4\pi Z_1^2 e^4}{m_e v^2} n_e \ln \frac{2m_e \gamma^2 v^2}{\hbar \omega_\varepsilon} \quad \beta^2 \qquad (3)$$

where $\omega_e = (4 \quad e^2 n_e / m_e)^{1/2}$ and $n_e = \Delta U^{th}/4$, m_e is the electron mass, $\beta = v/c$, where c is the speed of light, $\gamma \quad -\beta \quad \omega_e$ – the angular frequency of the electron gas oscillations of the crystal induced by the ion, and $n_e = n_e(x, y)$ is the (average) electron gas density.

The mean-square angular deviation of the ion due to its collisions with the electrons of the crystal and the ion beam divergence before its interaction with the crystal are taken into account [11]. The energy loss straggling effect is neglected [13, 14].

Due to the action of the centrifugal force on the channeled ion, the effective continuum interaction potential of the ion and the crystal is given by [9]

$$U_{eff}^{th}(x, y) \quad U^{th}(x, y) \quad \frac{p\upsilon}{R} y \qquad (4)$$

We chose the co-ordination system in which the centrifugal force is directed toward $-y$ axis.

The energy loss distribution of the channeled ions was obtained via the numerical solution of the ion equations of motion in the transverse plane and the computer simulation method [10, 11].

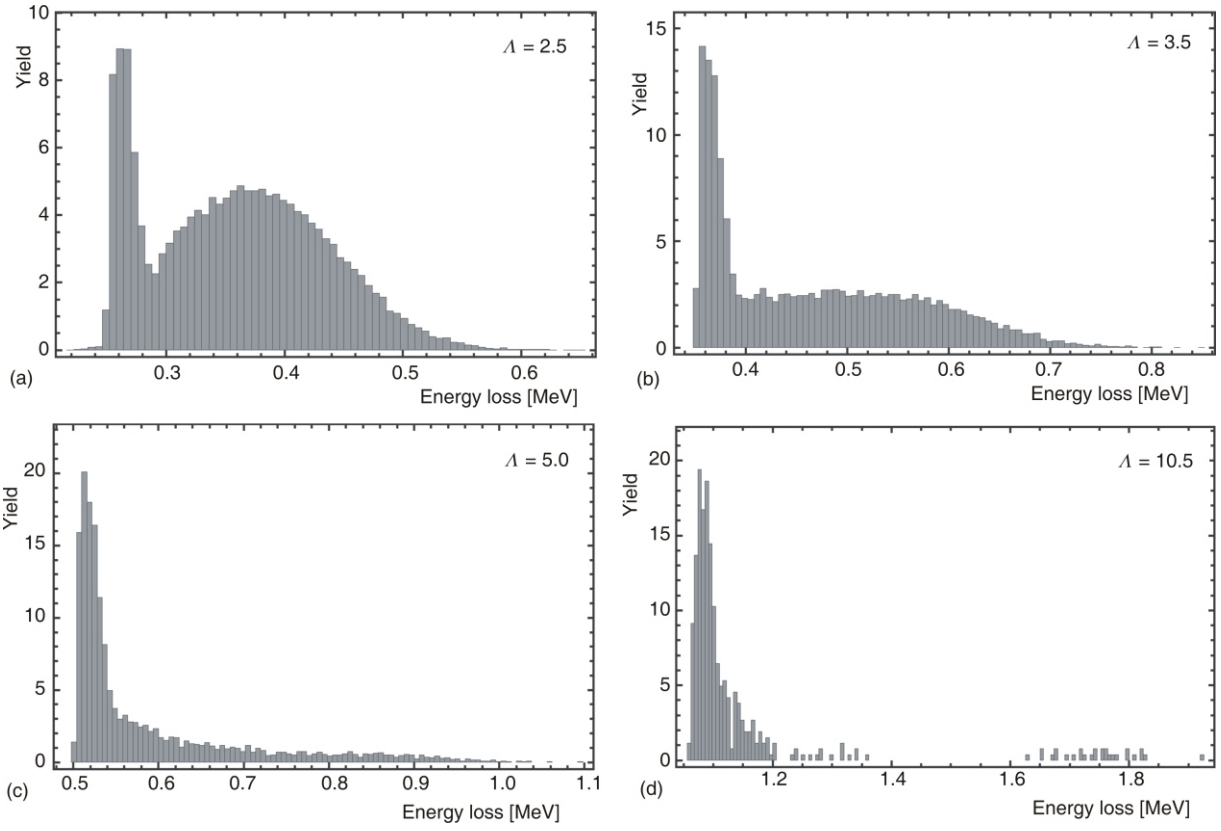

Figure 1. Energy loss distributions of 7 TeV protons channeled through the bent crystals (R = 50 m) for the reduced crystal thicknesses equal to (a) Λ = 2.5, (b) Λ = 3.5, (c) Λ = 5.0, and (d) Λ = 10.5

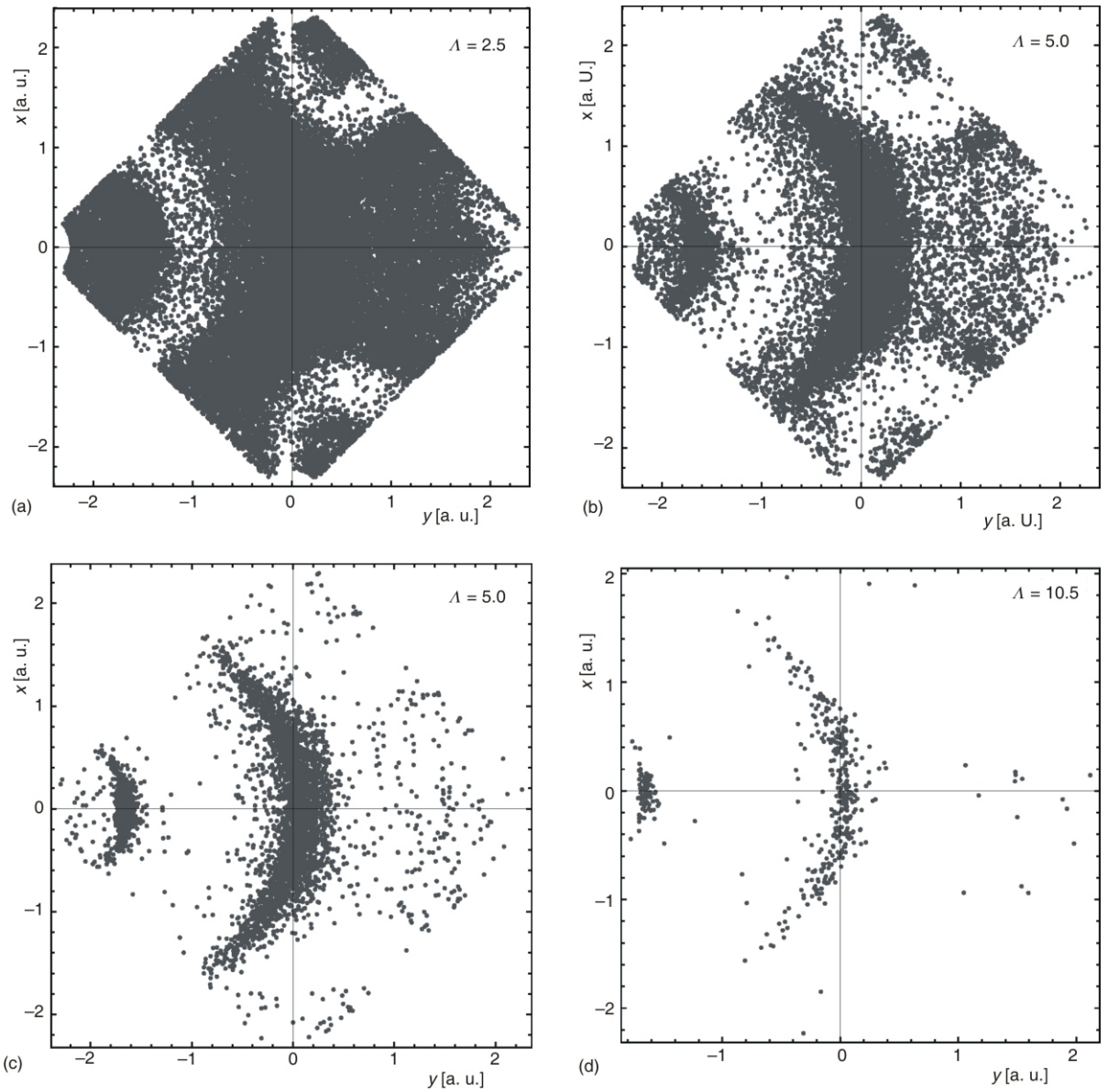

Figure 2. Protons in the impact parameter plane that generate the energy loss distributions given in fig. 1, for the reduced crystal thicknesses equal to (a) Λ = 2.5, (b) Λ = 3.5, (c) Λ = 5.0, and (d) Λ = 10.5

RESULTS AND DISCUSSIONS

As we have already mentioned, we shall analyze here the energy loss distributions of relativistic protons axially channeled in the bent <100> Si crystal, with the constant radius of curvature radius R = 50 m. The proton energy is 7 TeV, the thickness of the crystal, L, varies from 1 mm to 5 mm, which corresponds to the reduced crystal thicknesses, Λ, from 2.1 to 10.6. The distance between the atoms in the atomic string is 0.543082 nm [15]. The one-dimensional thermal vibration amplitude of silicon atoms is 0.00744 nm [16]. The number of atomic strings is 36, *i*. *e*. we took into account the atomic strings lying on the three nearest square coordination lines. The critical angle for the channeling is equal to 4.6 μrad.

The initial positions of the ions in the transversal plane were chosen uniformly within the crystal channel. The initial number of the ions was 2,019,241. The ions whose initial positions lie within the screening radius around the atomic strings defining the channel were treated as backscattered and disregarded. The proton beam divergence was taken to be $0.1\psi_c$ = 0.46 μrad.

Figures 1(a)-(d) show the energy loss distributions of the channeled protons for the reduced crystal thicknesses: Λ = 2.5, 3.5, 5.0, and 10.5, respectively, which correspond to the crystal thicknesses: L = 1.2, 1.6, 2.3, and 4.9 mm, respectively.

Figure 1(a) shows the energy loss distribution for Λ = 2.5 characterized by two peaks, the low energy one which is narrower and located at ΔE_1 = 0.27 MeV and the medium energy one, which is broader and located at

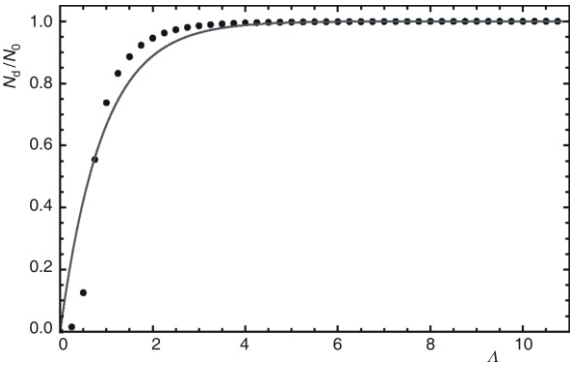

Figure 3. Dependence of number of the dechanneled protons on the reduced crystal thickness

$\Delta E_2 = 0.38$ MeV, and the high energy tail. In the energy loss distribution for $\Lambda = 3.5$, which is shown in fig. 2(b), one can clearly observe that the corresponding medium energy peak is diminishing, while the low energy peak remains, located at $\Delta E = 0.36$ MeV. The energy loss distributions for $\Lambda = 5.0$ and 10.5 confirm this trend, *i. e.* the low energy peaks remain, located at $\Delta E = 0.51$ MeV and $\Delta E = 1.08$ MeV, for $\Lambda = 5.0$ and 10.5, respectively, while, for $\Lambda = 10.5$, one can also observe small and broad high energy peak originating from the corresponding high energy tail.

Figures 2(a)-(d) show protons in the impact parameter plane that generate the energy loss distributions for the reduced crystal thicknesses: $\Lambda = 2.5$, 3.5, 5.0, and 10.5, respectively. It is clear from theses figures that the low energy peaks in the energy loss distributions are generated by the protons originating from the sickle like areas passing through the channel centre, corresponding to the low crystal electronic density, while the high energy tails are generated by the protons being around the atomic strings, corresponding to the high crystal electronic density.

The dechanneling function of protons, representing the dependence of the dechanneled protons number in the crystal on its depth (reduced crystal thickness) is shown in fig. 3. The analysis shows that it can be fitted with an exponential function: $N_d/N_0^{'} = 1 - \exp(-x/\Lambda_d)$, where N_d is the number of dechanneled protons, $N_0^{'}$ – the initial number of protons without the backscattered ones, and Λ_d – the fitting parameter, which represents the dechanneling range, while $1/\Lambda_d$ is the dechanneling rate. It follows that $\Lambda_d = 0.9$, which corresponds to the crystal thickness of 0.4 mm.

CONCLUSIONS

We have presented here in details the evolution of the energy loss distribution of 7 TeV protons channeled through the bent <100> Si crystals, with the constant curvature radius, $R = 50$ m, while the crystal thickness varies from 1 mm to 5 mm, corresponding to the reduced crystal thickness, Λ, from 2.1 to 10.6, respectively. The proton impact parameters generating the energy loss distributions are shown. The observed low energy peaks in the energy loss distributions originate from the sickle like areas passing through the channel centre while the high energy tails are generated by the protons being around the atomic strings.

The calculated dechanneling curve can be fitted with an exponential function, characterized by the dechanneling range $\Lambda_d = 0.9$, which corresponds to the crystal thickness of 0.4 mm.

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AUTHOR CONTRIBUTIONS

Theoretical analysis was carried out by N. Stojanov, S. M. Petrović, and N. B. Nešković. The manuscript was written by N. Stojanov and S. Petrović and the figures were prepared by N. Stojanov.

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РАСПОДЕЛЕ ЕНЕРГИЈСКИХ ГУБИТАКА ПРОТОНА ОД 7 TeV КАНАЛИСАНИХ У ЗАКРИВЉЕНИМ КРИСТАЛИМА СИЛИЦИЈУМА

Изучаване су енергијске расподеле релативистичких протона који су аксијално каналисани кроз закривљене <100> Si кристале, чији радијус кривине износи R = 50 m. Енергија протона износи 7 TeV, а дужина кристала се мења од 1 до 5 mm, што одговара редукованој дужини кристала од 2.1 до 10.6. Енергија протона је изабрана у складу са пројектом великог хадронског сударача Европске организације за нуклеарна истраживања у Женеви, Швајцарска. Енергијска расподела каналисаних протона добијена је помоћу метода компјутерске симулације користећи решења једначина кретања протона у трансверзалној равни. Дисперзија угла расејања јона која је последица његових судара са електронима кристала укључена је у прорачун.

Кључне речи: релативистичко каналисање, закривљен кристал, расподела енергијских губитака