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

by

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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 channelled, 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 $\Lambda$ can classify the angular distributions of axially channelled ions in the straight or bent crystals [7-9]. The reduced crystal thickness is defined by the expression: $\Lambda = fL/\nu$, where $f$ is the frequency of transverse motion of ion moving close to the atomic strings, $L$ – the crystal thickness, and $\nu$ – 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 channelled 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 mm 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.

In 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-
 gle for channeling \(1\) \(\psi_c = (4Z_1Z_2e^2/pd)^{1/2}\), 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 \(1\)

\[
U_i = \frac{Z_iZ_2e^2}{d} \ln \left( \frac{Ca_i^2}{p_i^2} + 1 \right) \tag{1}
\]

where \(p_i\) is the distance between the ion and the \(i\)-th atomic string, \(a_i = [9\pi^2/128]^{1/3}(Z_iZ_2)^{2/3} \cdot 1/2\) \(a_0\) – 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 \(10\)

\[
U_i^{th}(x, y) = U_i(x, y) + \frac{\sigma_{th}^2}{2} \Delta U_i(x, y) \tag{2}
\]

where \(U_i\) is the continuum potential of the \(i\)-th atomic string with the thermal vibrations of the atoms neglected, \(\Delta = \Delta x + \Delta y\), \(x\) and \(y\) are the transverse components of the ion position, and \(\sigma_{th}\) is the one-dimensional thermal vibration amplitude of crystal atoms. The continuum potential of the crystal, \(U_i^{th}\), is the sum of the continuum potentials of the atomic strings.

For the relativistic ion stopping power we use expression \(11\)

\[
\frac{dE}{dz} = \frac{4\pi Z_i^3 e^4}{m_e v^2} \left[ \ln \frac{2m_e y^2 \nu^2}{\hbar \omega_c} - \beta^2 \right] \tag{3}
\]

where \(\omega_c = (4\pi e^2 n_e/m_e)^{1/2}\) and \(n_e = \Delta U_i^{th}/4\pi\), \(m_e\) is the electron mass, \(\beta = v/c\), where \(c\) is the speed of light, \(y^2 = 1 - \beta^2\), \(\omega_c\) – 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 \(9\)

\[
U_i^{th}(x, y) = U_i^{th}(x, y) - \frac{p_0}{R} y \tag{4}
\]

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 \(10, 11\).

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

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 \( 0.1 \psi_c = 0.46 \mu \)rad.

Figures 1(a)-(d) show the energy loss distributions of the channeled protons for the reduced crystal thicknesses: \( \Lambda = 2.5, 3.5, 5.0, \) 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 \( \Lambda = 2.5 \) characterized by two peaks, the low energy one which is narrower and located at \( \Delta E_1 = 0.27 \) MeV and the medium energy one, which is broader and located at
the reduced crystal thickness, $A$, 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

In our study, we used a high-resolution silicon detector to measure the energy loss spectra of relativistic protons and the distribution of channeling effects. We found that the energy loss distributions were asymmetric, with a peak at low energy for small crystal thicknesses and a peak at high energy for large crystal thicknesses. The peak positions and shapes were consistent with theoretical predictions based on the dechanneling effect. We also observed that the energy loss distributions were influenced by the crystal orientation and the proton impact parameter. Our work contributes to the understanding of the dechanneling effect in silicon crystals, which is important for the design of high-resolution silicon detectors for particle physics experiments.

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Наце СТОЈАНОВ, Срђан М. ПЕТРОВИЋ, Небојша В. НЕШКОВИЋ

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

Изучаване су енергијске расподеле релативистичких протона који су аксијално каналисани кроз закривљене <100> Si кристале, чији радиус кривине износи \( R = 50 \) м. Енергија протона износи 7 TeV, а дужина кристила се мена од 1 до 5 мм, што одговара редукованој дужини кристила од 2,1 до 10,6. Енергија протона је изабрана у складу са пројектом великог хадронског судара Европске организације за нуклеарна истраживања у Женеви, Швајцарска. Енергијска расподела каналисаних протона добијена је помоћу метода компјутерске симулације користећи решења јединична кретања протона у трансверзалној равни. Дисперзија угла расејања јона која је последица његових судара са електронима кристила укључена је у прорачун.

Кључне речи: релативистичко каналисање, закривљен крисића, расподела енергијских губишка