Possibility of Deflecting Relativistic-Ion Beams by Bent Single Crystals

A. A. Greenenko[1)] and N. F. Shul'ga*

Ukrainian Research Center Kharkov Institute for Physics and Technology, ul. Akademicheskaya 1, Kharkov, 310108 Ukraine

Abstract—The propagation of high-energy ions through a bent single crystal near a crystallographic axis is investigated. The results of these investigations reveal that a new mechanism of ion-beam deflection is possible in this case. This mechanism is based on multiple ion scattering by atomic strings in a bent crystal. The results obtained from a computer simulation of the effect are also presented. The effect is shown to depend strongly on the particle charge.

1. INTRODUCTION

The deflection of beams of high-energy positively charged particles via the mechanism of planar channeling in bent crystals is a well-studied effect, which is used in practice [1, 2]. In [3–5], it was indicated that there exists another mechanism of beam deflection by a bent crystal, that which is based on the multiple scattering of particles by atomic strings. A feature peculiar to this mechanism is that, in scattering by atomic strings, beam deflection is possible both for channeled and for above-barrier particles; at the same time, only for channeled particles is this possible in the case of motion along bent crystallographic planes. Moreover, a beam incident on a bent crystal at a small angle with respect to a crystallographic axis can undergo both deflection and splitting. It is important to note that not only elementary-particle beams but also beams of multiply charged ions can be deflected by bent crystals [6]. In the latter case, the value of the charge affects substantially the deflection of the charged-particle momentum [6, 7]. In the present study, we analyzed the mechanism of deflection of relativistic-ion beams due to multiple particle scattering on atomic strings in a bent crystal.

2. SIMULATION PROCEDURE AND BASIC RESULTS

The possibility of deflecting ion beams that traverse a bent crystal near a crystallographic axis was considered both analytically and on the basis of a numerical simulation. The problem at hand can be treated analytically in the case where the conditions of dynamical chaos are realized in the scattering process [8]. But in the general case, it is necessary to apply methods of a numerical simulation. For this purpose, we developed a computer code for simulating the propagation of charged particles through a bent crystal near a crystallographic axis [4, 8]. The propagation of particles through a crystal is considered as a step-by-step two-dimensional motion in the plane orthogonal to the direction of the crystallographic axis in the total field of atomic strings. A continuous potential of atomic strings can be computed on the basis of the Mollier approximation for the potential of an individual atom. At each step, we computed both coherent and incoherent particle scattering, the former being caused by an averaged continuous potential. Incoherent scattering is associated with the distinction between the actual potential of a string and the averaged potential. This distinction is due to the thermal displacements of lattice atoms from equilibrium positions and to lattice electrons. Incoherent scattering changes the transverse energy of the scattered particle. It is taken into account under the assumption of a Gaussian distribution of computed quantities.

An analytic consideration of charged-particle propagation through a bent crystal near a crystallographic axis shows [8] that the effect of beam deflection by a crystal is possible under the condition

$$\alpha = \frac{L}{R_{\psi_c}}\frac{l_\perp}{R_{\psi_c}} < 1, \qquad (1)$$

where L is the crystal thickness, R is the radius of curvature of its bend, ψ_c is the critical angle of axial channeling, and $l_\perp$ is the length over which the distribution of particles with respect to the azimuthal angle is established as the result of multiple scattering. For $\psi \le \psi_c$, we have the approximate relation $l_\perp \approx (\psi_c n d a_{TF})^{-1}$, where n is the density of atoms, d is the interatomic spacing along the direction of motion (z axis), and a_{TF} is the radius of screening of the atomic potential.

Since $\alpha \sim \psi_c^{-3}$ and $\psi_c \sim \sqrt{Z_i}$, the mechanisms of propagation through a bent crystal can be very different

[1)] Ukrainian Research Center Kharkov Institute for Physics and Technology, ul. Akademicheskaya 1, Kharkov, 310108 Ukraine and Belgorod State University, Studencheskaya ul. 12, Belgorod, 308007 Russia.

* e-mail: shulga@kipt.kharkov.ua

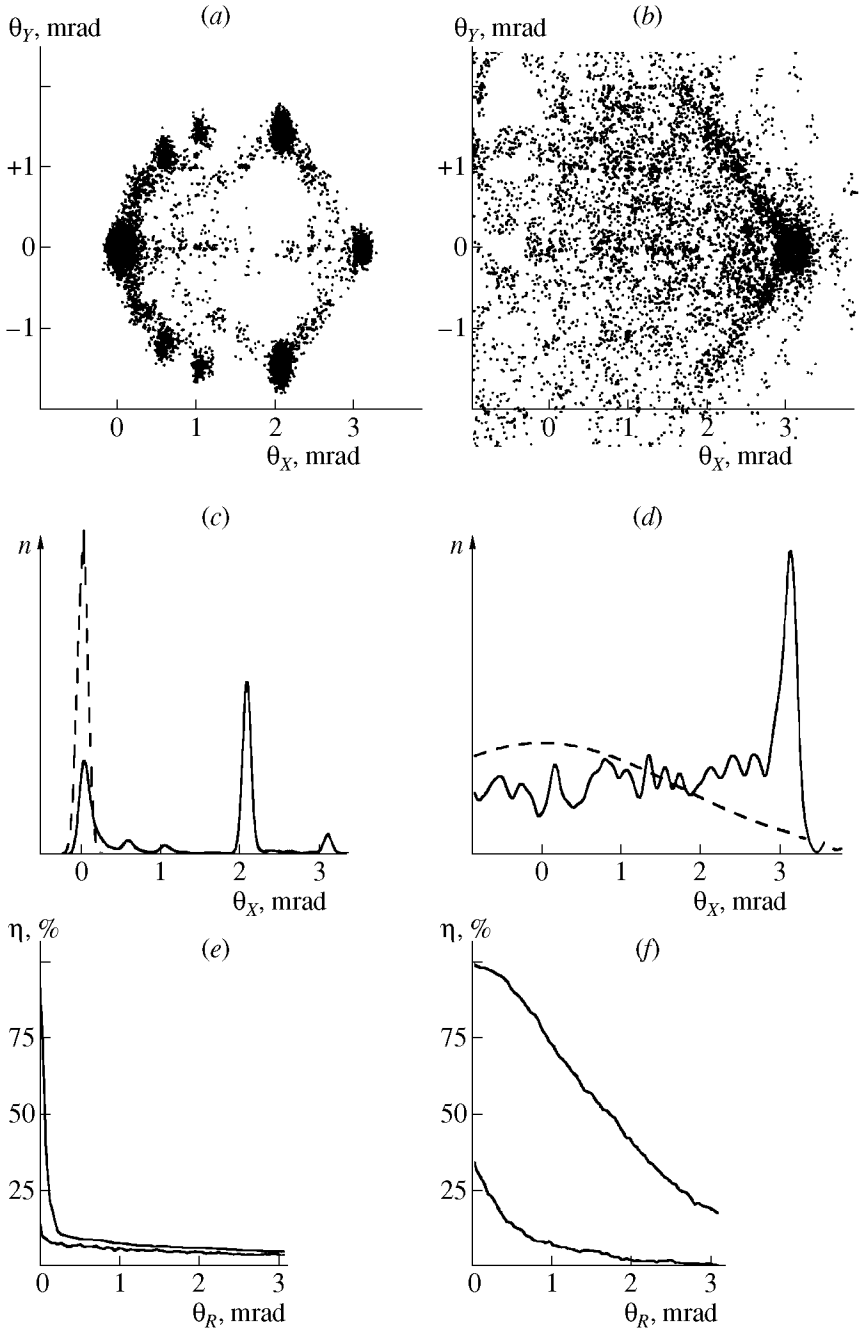

Fig. 1. Propagation of 450-GeV beams of (*a*, *c*, *e*) protons and (*b*, *d*, *f*) U^{+92} ions through a bent silicon crystal whose thickness is of $L = 3$ cm and whose radius of curvature is of $R = 10$ m near its ⟨110⟩ axis: (*a*, *b*) angular distributions of particles leaving the crystal, (*c*, *d*) horizontal profile of the beam leaving the crystal, and (*e*, *f*) fractions of (upper curves) deflected and (lower curves) hyperchanneled particles versus the crystal thickness. The dashed curves in Figs. 1*c* and 1*d* represent the profiles of the beams that traversed a 3-cm layer of amorphous silicon. The coordinates of the initial-beam center, the beam divergence, the coordinates specifying the crystal-axis direction at the downstream surface of the crystal, the beam dimensions, and the observation base were, respectively, $(\theta_X, \theta_Y) = (0, 0)$, 3×10^{-6} rad, $(\theta_X, \theta_Y) = (3.1, 0, 0)$ mrad, 1×2 mm^2, and 4 m.

for protons and for multiply charged ions. By way of example, we indicate that, for a beam of 450-GeV particles incident on a silicon single crystal along the ⟨110⟩ axis at $L = 3$ cm and $R = 10$ m (which corresponds to the parameters of the CERN experiment studying the axial deflection of protons [9]), we have $\alpha_p = 80$ for protons and $\alpha_U = 0.1$ for uranium ions. Taking into account the condition in (1), we conclude that, for the above values of the beam and crystal parameters, the mechanism of deflection via multiple scattering on single-crystal strings must be operative for ions and inoperative for protons. This theoretical prediction is fully

confirmed by the results of a numerical simulation (for a proton beam, the results of the simulation are in good agreement with the experimental data from [9]). Figure 1 shows the results of our computer simulation for the above conditions.

Our results demonstrate that the angular distributions of protons that traversed a single crystal differ considerably from the analogous distribution for multiply charged uranium ions. The direction of the crystallographic axis at the downstream surface of the crystal is taken here to correspond to $\theta_R = 3$ mrad. In the case of ions, a significant fraction of beam particles (about 20%) are deflected through this angle, following the bend of the crystallographic axis. It is predominantly the above-barrier particles that undergo deflection under such conditions (see Fig. 1*f*). Among protons, only the hyperchanneled particles are deflected in the case being considered (see Fig. 1*e*). Initially, the fraction of hyperchanneled protons is much less than that in the case of ions because the depth of the two-dimensional potential well is much greater for ions than for protons. The results of our simulation reveal, however, that the process of dechanneling is more vigorous for ions than for protons; as a result, the beam of uranium ions leaving the crystal does not contain hyperchanneled particles. Our analysis of the numerical data shows that this effect is due to a sharp intensification of incoherent scattering on lattice electrons with increasing particle charge. Thus, the deflection mechanism associated with multiple scattering on bent atomic strings is operative for multiply charged ions. Indeed, strong incoherent scattering, which suppresses the deflection of hyperchanneled particles (both in the axial and in the planar case), leaves the possibility for the axial deflection of above-barrier particles.

Symmetric peaks in the distribution of protons (see Figs. 1*a*, 1*c*) are associated with particles captured in planar channels. This capture occurs when the deflected particles cease to follow the axis and results in the possible splitting of the beam into several isolated fractions. A gradual escape of particles from the trajectory along the axis occurs when the deflection conditions are impaired—that is, when the parameter α approaches unity with increasing crystal thickness. The fractions captured by planes are localized when the capture of new particles is terminated—that is, when $\alpha > 1$; this inequality can be considered as the condition under which the effect of beam spitting is realized.

Thus, the propagation of relativistic multiply charged ions through a bent crystal differs considerably from the propagation of protons and must be considered separately. The results obtained here show that the above effects can be investigated at the GSI ion accelerator.

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