Spatial focusing of 1-GeV protons by a curved single crystal

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Experiments show that a single crystal curved into a cylinder can select from a broad beam particles which arrive at the focus of the crystal. The width of the focus of the selected 1-GeV protons is $\text{FWHM}_{ch} = 0.65$ mm when a silicon crystal is curved to a radius of curvature of 2 m. The width of the direct beam in the focal region is $\text{FWHM}_r = 15.4$ mm.

Our previous experiments[1,2] have shown that a curved single crystal is capable of efficiently capturing particles into a channeling regime in an interval of angles much greater than the Lindhard angle. As they leave the crystal, the particles which have been captured into the channeling regime have a narrower angular distribution; i.e., an angular focusing occurs.[2] Our purpose in the present letter is to study the possibility of achieving a spatial focusing of a charged-particle beam with the help of a curved crystal.

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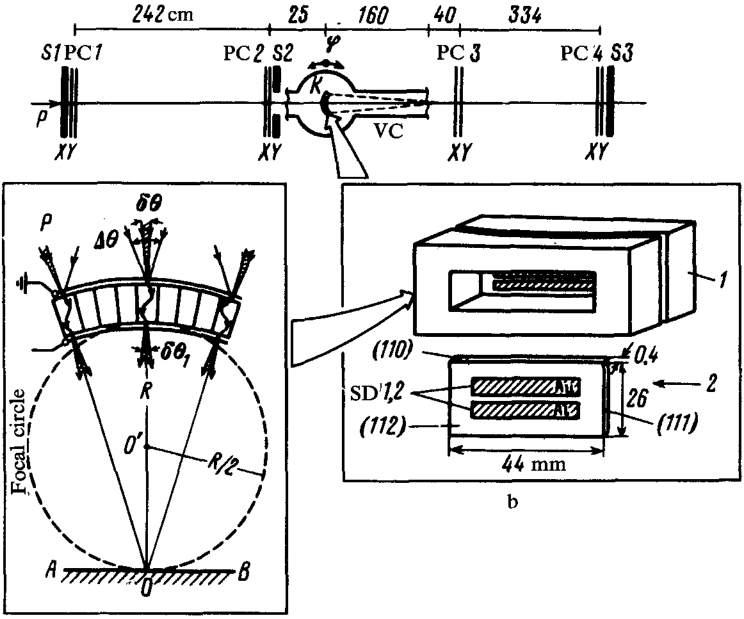

a b

FIG. 1. The general experimental layout. S1–S3—Scintillation counters; PC1–PC4—proportional chambers; VC—vacuum chamber; C—crystal; P—proton beam. a: Spatial-focusing principle (also shown here are the electrodes of detector SD1; the polarity is opposite for detector SD2). b: Design of the bending device; parameters of the crystal; and of positions of the detector zones (SD1, 2).

The present experiments were carried out in a 1-GeV proton beam at the synchrocyclotron of the Leningrad Institute of Nuclear Physics. The experimental arrangement is shown in Fig. 1. The silicon single crystal is curved into a cylinder ($R = 2$ m) with (111) crystallographic planes oriented normal to the concave (or convex) face of the crystal, which doubles as a surface-barrier detector (SD1, 2).[1)] A broad beam (spanning the entire crystal) with an angular divergence $\Delta\theta_{1/2} = 8$ mrad is directed toward the crystal. The use of the crystal as a semiconductor detector makes it possible to identify ("tag") the channeled particles, by virtue of their anomalously low ionization loss. Since, as the crystal is curved into a cylinder, the crystallographic planes which are normal to the faces fan out with a center at a distance equal to the radius of curvature of the crystal (Fig. 1a), the particles channeled between these planes are focused at point O. The resulting arrangement is similar to that of a Koshua focusing spectrometer, quite familiar in x-ray or γ-ray spectroscopy.[3] Since the corresponding angles on the focal circle (the circle of radius $R' = R/2$ which passes through the point O' and which is tangent to the curved crystal) are roughly equal, the continuations of the oblique planes (those inclined with respect to the large faces) and the particles channeled along them are also focused. The width of the focus is determined by the angular divergence ($\delta\theta_1$) of the particles emerging from the channels in the crystal.

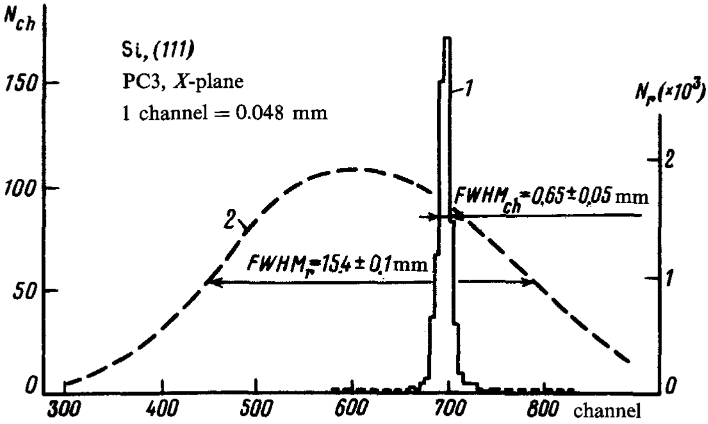

FIG. 2. Spatial distribution of the beam in the X-plane of PC3. 1—With selection based on the condition that the signal from the detector have a small amplitude (0.3–0.6 of the most probable value for a random phase); 2—without selection (the direct beam).

The measurement process consists of selecting from the beam leaving the crystal the particles with a small ionization loss (0.3–0.6 of the most probable value of the loss for a random phase) and observing the spatial distribution of these particles in a proportional chamber at the focus of the curved crystal. As a result of this selection of particles (curve 1 in Fig. 2), we obtain a peak with a width of 0.65 ± 0.05 mm, which corresponds to the angular divergence determined by the Lindhard angle for the given crystallographic plane.[2)] The contrast of the focus (the effect-to-background ratio) is ~ 34.

A natural consequence of this result is that it is also possible to use a similar device, but with a backward motion of the particles (an analog of a Dumond focusing spectrometer[3]), to study the distribution of the intensity of the particle emission along an extended source (AB in Fig. 1a).

[1)]Two independent detectors (SD1, 2) are arranged on the crystal. The two are at different heights, and their p-n junctions are on opposite faces of the crystal. The two detectors provide mutually complementary information, which eliminates possible effects from surface regions ("dead" layers).

[2)]Taking into account multiple scattering by the window of the vacuum chamber (VC) and in the air-filled gap in front of PC3, we find $\mathrm{FWHM}'_{ch} = 0.60 \pm 0.05$ mm, corresponding to an angular divergence $\delta\theta_1 = (3.0 \pm 0.25) \times 10^{-4} = 1.7\, \psi_L$ of the particles emerging from the channel. Here $\psi_L = 1.72 \times 10^{-4}$ is the Lindhard angle for the (111) plane in silicon, and $E_r = 1$ GeV.

[1]V. A. Andreev, V. V. Baublis, E. A. Damaskinskiĭ, A. G. Krivshich, *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **36**, 340 (1982) [JETP Lett. **36**, 415 (1982)].

[2]V. A. Andreev, V. V. Baublis, E. A. Damakinskiĭ, *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 54 (1984) [JETP Lett. **39**, 61 (1984)].

[3]O. I. Sumbaev, Kristall-difraktsionnye gamma-spektrometry (Crystal-Diffraction Gamma Spectrometers), Gosatomizdat, Moscow, 1963.

Translated by Dave Parsons