SSCL-Preprint-477

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July 1993
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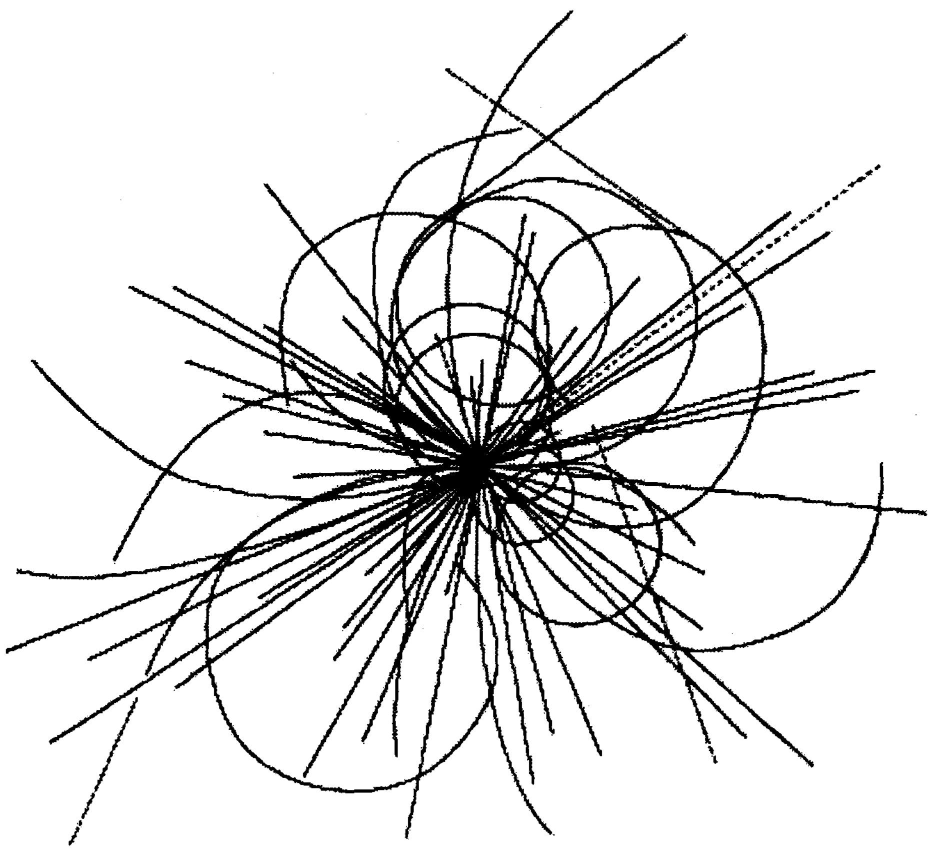

Superconducting Super Collider Laboratory

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July 1993

*To be presented at the ICACS – 15 Conference in London, Ontario on July 26, 1993.
‡Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

EFFECTS ON CHANNELING OF RADIATION DAMAGE DUE TO 28-GeV PROTONS

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ABSTRACT

For an irradiation of 2.9×10^{19} protons at a beam energy of 28 GeV, the channeling minimum yield in a silicon single crystal increased from 2.3% to 4.1%. The radiation damage occurred with a proton fluence of $(4.1 \pm 1.4) \times 10^{20}/cm^2$. The degradation was measured with MeV-range He ions using Rutherford back-scattering. The relevance to bent crystal extraction of TeV beams is discussed.

1. Introduction

Deflection of particles by channeling in bent crystals has been observed up to an energy of 800 GeV at Fermilab [1]. Accelerator extraction using channeling was first demonstrated at Dubna with 4–7.5 GeV protons [2]. Since then proton beams have been extracted at 70 GeV at Serpukhov [3] and at 120 GeV/c at CERN [4]. Crystal extraction of a small fraction of the circulating beam is being considered for the Superconducting Super Collider (SSC) [5] and for the CERN Large Hadron Collider (LHC) [6]. Extraction studies directed toward developing that capability are now underway at the Fermilab Tevatron and the CERN SPS.

The ability of a crystal to survive radiation damage is an important consideration in its use for extraction. Radiation damage studies on silicon crystals used in a high-energy channeling experiment were carried out by our Fermilab, Chalk River, SUNY-Albany collaboration [7] and showed that a fluence of 400-GeV protons of approximately $10^{17}/cm^2$ did not destroy the crystal's ability to deflect particles. Detectors implanted in such crystals no longer worked because of radiation damage. MeV channeling was also observed with Rutherford back-scattering (RBS) following an irradiation to $10^{18}/cm^2$ using 28-GeV protons at the Brookhaven National Laboratory Alternating Gradient Synchrotron [8] (BNL AGS). A Serpukhov extraction device [9] worked after an exposure to a fluence of $10^{19}/cm^2$. These studies are summarized in Table 1. The experiment reported here achieved an exposure to a fluence of greater than $10^{20}/cm^2$.

2. Irradiation

This note reports the first observation of a significant degradation in channeling caused by radiation with GeV particles. The increase in crystal disorder for 2-MeV He ions was small, approximately 2%, compared to a minimum yield of 2.3% in non-irradiated silicon. It occurred following an irradiation to an exposure of 2.9×10^{19} protons. Achieving such an exposure requires sustained access to a very high intensity beam. Since the energy loss and the cross section are not strongly energy dependent, the beam energy is not important and an exposure at 28 GeV should be relevant to TeV channeling.

The irradiation was conducted over a three-month period in 1986 at the AGS using the beam upstream of the neutrino production target in the U Line. Integrating intensity monitors measured the exposure. The peak flux was determined by measuring the radioactivity in an aluminum foil wrapping surrounding the silicon.

The crystal was high resistivity zone-refined silicon. The 15 mm × 9 mm slab was 1 mm thick. The surface normal was midway between a <110> axis and a <111> axis.

The crystal was near the beam final focus. Beam optics estimates indicated a spot diameter of about 1 mm. The photographs in Figure 1, taken after etching, show the discoloration of the crystal due to the beam spot. It is not clear what gave rise to the appearance of the spot, but it is interesting that it is visible on both sides. The measured diameter from the photograph is 3.1 mm. While the center of the beam was on the crystal, some of the beam did not strike it.

The autoradiograph was obtained by placing the aluminum foil directly on the emulsion of a piece of Polaroid Type 57 film for 10 min. This minimized broadening due to separation of the foil from the emulsion. The developed emulsion was scanned using a densitometer with a 1×2 mm aperture. Scans were taken in the 1-mm direction. Raw film densities were adjusted using the published response of the film. Beam profiles were taken parallel and perpendicular to the nearest edge of the crystal. These agreed in normalization and width to a good approximation and were well-fitted by the Gaussian distribution shown in Figure 2 with $\sigma = 1.1$ mm. That distribution has been normalized to the channeling damage distribution discussed in Section 3 and superimposed on the minimum yield for the undamaged crystal. The visible surface damage and location based on the photograph agreed with the pattern observed using the autoradiograph. The beam spot diameter found from Figure 1 is also shown on Figure 2.

Estimates of the peak fluence are limited principally by the uncertainty of the width distribution based on the different measurements. The peak fluence based on the autoradiograph distribution was $(4.1 \pm 1.4) \times 10^{20}/cm^2$.

3. Examination Using Low Energy Back-Scattering

Crystal damage was examined with RBS using a 2-MeV singly-ionized helium beam from the SUNY-Albany dynamitron. The second electron was stripped away at the surface so the back-scattering was that of an alpha particle. The He beam was collimated into a circular spot about 1 mm in diameter. The peak fluence on the crystal from the dynamitron was less than $10^{16}/cm^2$.

The normalized back-scattering yield, χ, is the ratio of the back-scattering at some angle divided by the yield in a random (non-aligned) direction. The yield was measured as a function of the angle to the <110> axis. The <110> axis was used because it has the smallest minimum yield, so changes are more noticeable.

The radiation-induced crystal disorder (see Bogh [10] and Chu et al. [11]) is closely related to the minimum yield. The disorder is $[\chi(0) - \chi_v(0]/[1 - \chi_v(0)]$, where $\chi(0)$ is the minimum yield for the damaged portion of the crystal and $\chi_v(0)$ is the minimum yield for a non-irradiated (virgin) part. The observed value for $\chi_v(0)$ was 2.3% for 2.0-MeV He ions. The average value for $\chi(0)$ at the maximum point of damage was 4.1%. Figure 2 shows the minimum yield for scans parallel and perpendicular to the nearest edge of the crystal, along with Gaussian fits to the data. The Gaussian widths are $\sigma_h = 1.0$ mm for the perpendicular case and $\chi_v = 1.4$ mm for the parallel one. The width of the perpendicular scan is consistent with the autoradiograph. The parallel scan width is larger. The difference between the two is probably consistent with uncertainties in system parameters such as the dynamitron phase space.

The minimum yield was also measured as a function of dynamitron energy. This gives information on the radiation-damage defects. The minimum yield should rise with energy for dislocations [12], remain flat for stacking faults, and drop for interstitial atoms. Figure 3 shows the energy dependence. The minimum yields for both the damaged and the undamaged portions rise with energy. It is possible that this may mean the energy windows for the RBS measurements were not perfectly adjusted. Therefore it is unwarranted to attribute the damage to dislocations on the basis of this information alone. In collaboration with the Petersburg Nuclear Physics Institute we are now studying line broadening with double x-ray scattering to look for dislocations.

4. Relation to Extraction in the 10–20 TeV Range

This study is the first to show clear evidence of radiation damage from a high-energy beam that affected the channeling capability. Several questions remain. One is how the fluence of this study relates to situations likely to be encountered in trans-TeV extraction. The second is whether damage studies done in the MeV regime (or with double x-ray scattering) relate to dechanneling in the TeV regime.

The SSC beam at the crystal extraction point will have a vertical size of 0.16 mm (1 σ). The SSC crystal extraction proposal (SSC EOI-14) is based on a flux on the crystal of 10^8/s. The deflection of the beam into the crystal will be on the order of 1 μm. This results in a fluence on the crystal of $3 \times 10^{18}/\mathrm{cm}^2$ in one day. The maximum fluence for this measurement is consistent with a three-month exposure on the proposed SSC crystal septum. Since the spot size is expected to be several millimeters along the crystal edge, small translations could extend the crystal life.

The best way to study the impact of radiation damage on extraction devices is to look at high-energy dechanneling in crystals that have been exposed to high-energy beams in a controlled way. Several of our studies in the hundred-GeV regime at lower fluences used this approach. However, measurements at the SSC or LHC are a decade away. By then these devices must be ready to operate. For dislocation damage, even at 900 GeV, there is risk in extrapolating over a scale of 10 to 20, since dislocation dechanneling rises with energy.

A second problem is that it is difficult to achieve these fluences in a controlled way, difficult to monitor the micron-wide damaged area, and difficult to study dechanneling except in the extraction device itself. One possible attack is very accurate observation of the extracted flux with time. This in turn requires accurate monitoring of the incident beam and the beam conditions.

Biryukov et al. [13] have analyzed dislocation effects on 20-TeV bent-crystal dechanneling using, in part, theories developed for MeV dislocation studies. They consider A and B type dislocation loops as well as linear dislocations and give formulas for the impacts of various dislocation types. They find the impact of dislocation loops is substantially different in the Tev range compared to lower energies. Only the large A type loops are significant, so A loop density must be kept small. Linear dislocation densities must be $1/cm^2$ or smaller. Their formulation can also be used to study the impact of radiation-induced dislocations. Thus, if studies find that some of the damage observed in our MeV channeling investigation is due to dislocations, it should be possible to infer the significance for TeV applications.

Dechanneling due to radiation damage-induced point defects should be less significant than dislocation dechanneling in the TeV range. An analysis by Baker [8] of the fractional defect level induced by 100-GeV protons suggests it approaches one for fluences in the 10^{20}–$10^{21}/cm^2$ range. However some annealing must also take place. Annealing of radiation-induced vacancies is complex (see, for instance, Hayashi et al. [14]). In our study the crystal retained almost all of its ability to channel after an exposure of $4.1 \times 10^{20}/cm^2$, indicating it was still a very ordered structure. No care was taken to keep the sample at constant temperature. However damage measurements made over several years have not indicated any further annealing.

5. Summary

This experiment has shown the first significant evidence for high-energy radiation damage effects on channeling in a crystal. The problem is to characterize that damage. If it is due to dislocations and some radiation-induced dislocation density can be inferred, then it will be possible to relate the observed damage more directly to trans-TeV dechanneling.

6. Acknowledgments

The authors acknowledge the assistance of A. Carroll, J. Cumming, and D. Lazarus of BNL in performing the AGS irradiation, and A. Haverall, S. Hashimoto, Q. Xiao, and K. Umazawa of SUNY-Albany in the dynamitron RBS measurements. We have had helpful discussions with J. Ellison of the University of New Mexico and V. Samsonov of the Petersburg Nuclear Physics Institute. This work was supported in part by the U. S. Department of Energy under contracts DE-AC35-89ER40486 and DE-AC02-76CH0300.

Table 1. Summary of Some Radiation Damage Studies.

Year Published Reference	Location	Energy (GeV)	Exposure (part./cm^2)	Technique	Result
1983 (7)	Fermilab	400	1.0×10^{17}	Irradiated Bent Crystal	Changed Dechanneling Length
1983 (7)	Fermilab	400	6×10^{16}	RBS, Bent and Not Bent	Minimum Yield Increase <1%
1987 (8)	Fermilab	400	5×10^{16}	Irradiated Bent Crystal	Little or No Damage
1987 (8)	BNL	28	1×10^{18}	RBS	No Radiation Damage Effect
1992 (9)	Serpukhov	70	1×10^{19}	Extraction	No Noticeable Efficiency Deterioration
1983	BNL	28	4.1×10^{20}	RBS	Minimum Yield Increase (1.8 ±0.6)% at 2 MeV

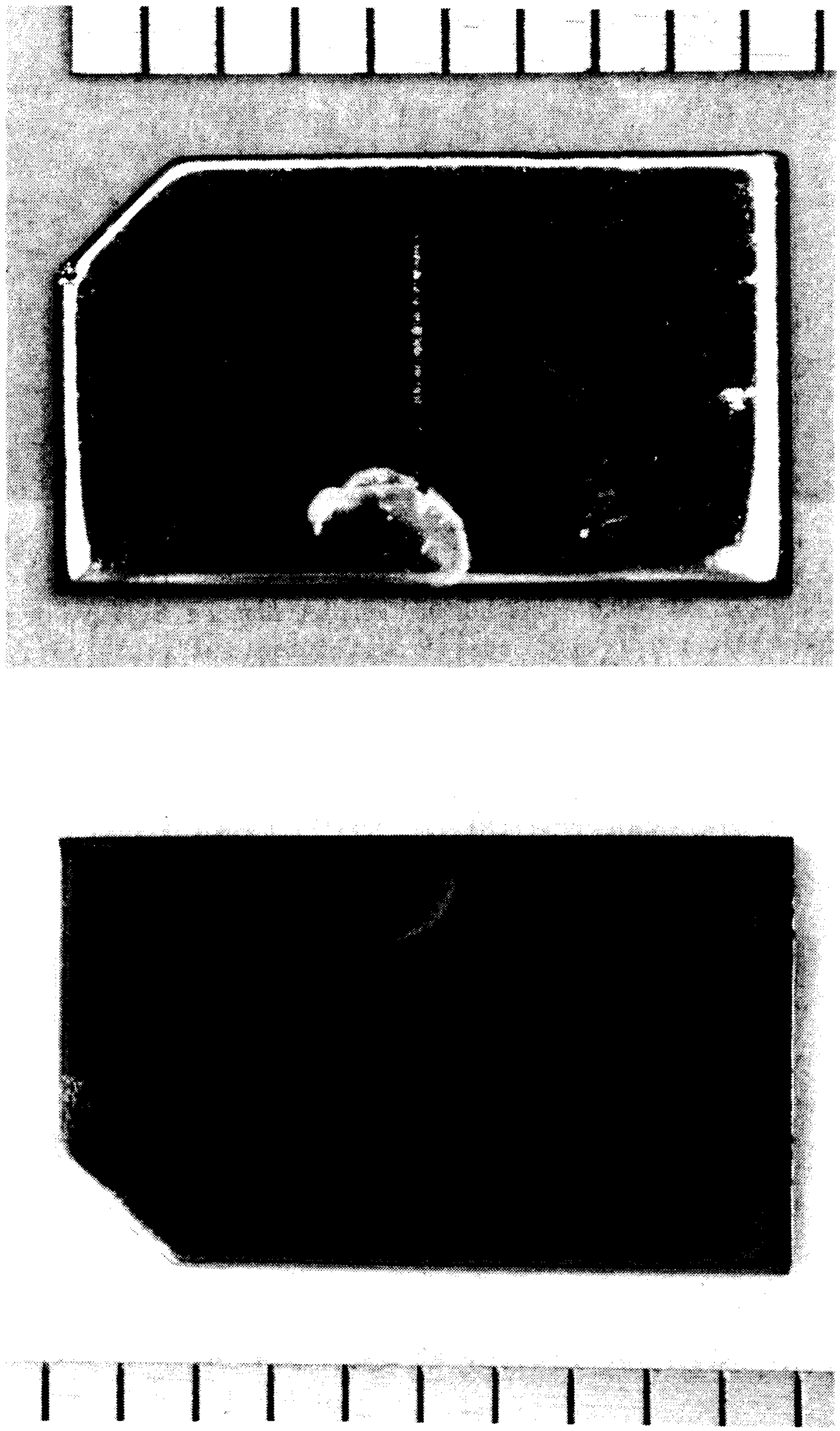

Figure 1. Photograph of the exposed crystal from two sides. (It is not known which side was upstream.) The scale divisions are 1/16th of an inch.

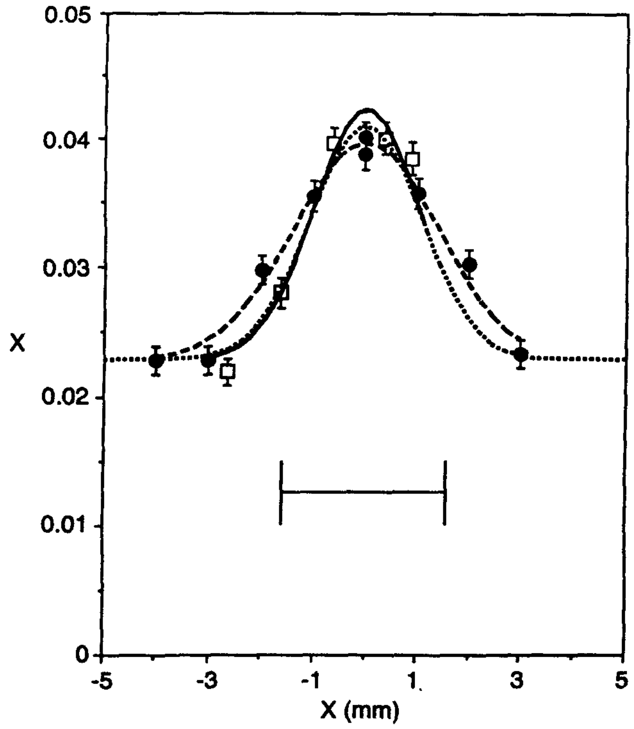

Figure 2. Minimum yield due to radiation damage. Squares are for a scan perpendicular to the crystal edge intercepting the proton beam (horizontal in Figure 1), filled circles are for the parallel scan. Fits are also shown (solid for perpendicular, dashed for parallel). The adjusted parallel scan autoradiograph fit is also shown as a dotted line. The horizontal bar near the bottom shows the diameter of the spot measured from the photograph.

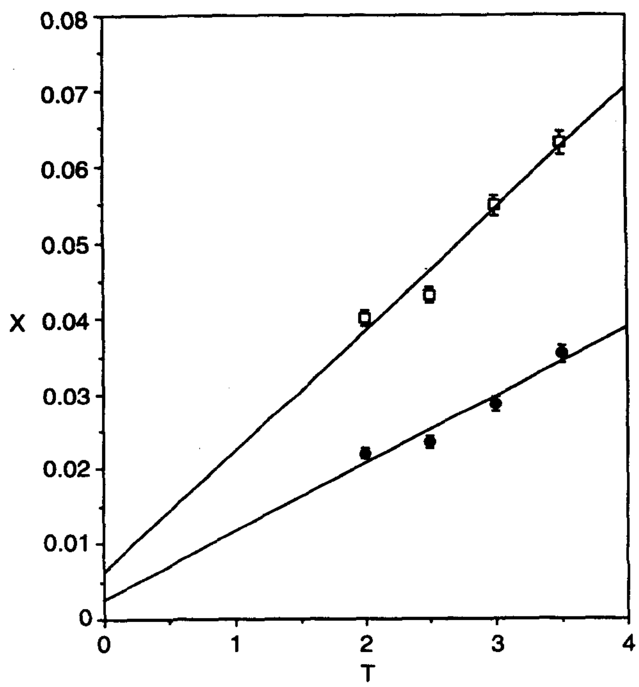

Figure 3. Minimum yield as a function of dynamitron energy at the center of the damage spot (open squares). The filled circles show the behavior for an undamaged portion of the crystal.

References:

[1] S.I. Baker, R.A. Carrigan, Jr., R.L. Dixon, H.C. Fenker, R.J. Stefanski, J.S. Forster, R.L. Wijayawardana, and S. Reucroft, Nucl. Instr. and Meth. **A248**, 301 (1986).

[2] V.V. Avdeichikov et al., JINR 1–84, Dubna (1984). English translation: Fermilab FN-429 (1986).

[3] See, for example, A.A. Asseev, M. Bavizhev, E.A. Ludmirsky, V.A. Maisheev, and Yu. S. Fedotov, Nucl,. Instr. and Meth. **A309**, 1 (1991).

[4] W. Scandale, private communication (1992). CERN Bulletin, July 20, 1992.

[5] R.A. Carrigan, Jr., T.E. Toohig, and E.N. Tsyganov, Nucl. Instr. and Meth. B48, 167 (1990). S.E. Anassontzis et al., Nucl,. Phys. B27 (Proc. Suppl.), 352 (1992). Fermilab E-853 (1991). SSC Expression of Intent, EOI-14 (1990).

[6] W. Scandale, et al., Status Report on RD22: Crystal Extraction at the SPS, CERN/DRDC 92–51.

[7] G.H. Wang, P.J. Cong, W.M. Gibson, C.R. Sun, I.J. Kim,. S. Salman, M. Pisharody, S.I. Baker, R.A. Carrigan, Jr., J.S. Forster, and I.V. Mitchell, Nucl., Instr. and Meth. **218**, 669 (1983).

[8] S.I. Baker, p. 391 in Relativistic Channelling, eds. R.A. Carrigan, Jr., J.A. Ellison (Plenum, New York, 1987).

[9] Yu, A. chesnokov, N.A. Galyaev, V.I. Kotov, S.V. Tsarik, V.N. Zapol'sky, Proc. of the XV Int. Conf. on High Energy Accelerators (Hamburg-1992).

[10] E. Bogh, Can. J. Phys, **46**, 653 (1968).

[11] W.K. Chu, J.W. Mayer and M.A. Nicolet, Backscattering Spectroscopy (Academic Press, New York, 1978) p. 257.

[12] L.C. Feldman, J.W. Mayer and M.A. Nicolet, Backscattering Spectroscopy (Academic Press, New York, 1978) p. 257.

[13] V.M. Biryukov, M.D. Bavizhev, and E.N. Tsyganov, SSCL-N-777 (1991).

[14] N. Hayashi, R. Suzuki, M. Hasegawa, N. Kobayashi, S. Tanigawa, and T. Mikado, Phys. Rev. Lett. 70, 45 (1993).