HELMHOLTZ

IONIZATION LOSS FOR MEASUREMENTS OF THE DECHANNELING LENGTH OF ELECTRONS

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Abstract

- A new method for the experimental study of ionization loss of relativistic negatively charged particles moving in a crystal in the channeling regime using a semiconductor surface-barrier detector with smoothly tunable thickness of the depleted layer is proposed. The ionization loss can only be measured in the depleted layer of the detector. The thickness of the depleted layer in a flat semiconductor detector can be smoothly regulated by the value of the bias voltage of the detector. Therefore, the energy distribution of the ionization loss of relativistic particles which cross the detector and move in the channeling regime in the detector crystal can be measured along the path of the particles at variation of the bias voltage of the detector. Thus, the dechanneling length of electrons in a crystalline detector can be measured [1,2].

- This project has received funding through the MSCA4Ukraine project, which is funded by the European Union.

- 1. A.V. Shchagin, G. Kube, S.A. Strokov, W. Lauth. Surface-barrier detector with smoothly tunable thickness of depleted layer for study of ionization loss and dechanneling length of negatively charged particles channeling in a crystal. Preprint, 2022. http://arxiv.org/abs/2211.01913
- 2. S.V. Trofymenko, I.V. Kyryllin. On the ionization loss spectra of high-energy channeled negatively charged particles. Eur. Phys. J. C 80 (2020) 689.

Dechanneling length of electrons

H. Backe, W. Lauth. Channeling experiments with sub-GeV electrons in flat silicon single crystals. Nuclear Instruments and Methods in Physics Research B 355 (2015) 24–29.

Experimental data at electron energy about and below 1 GeV

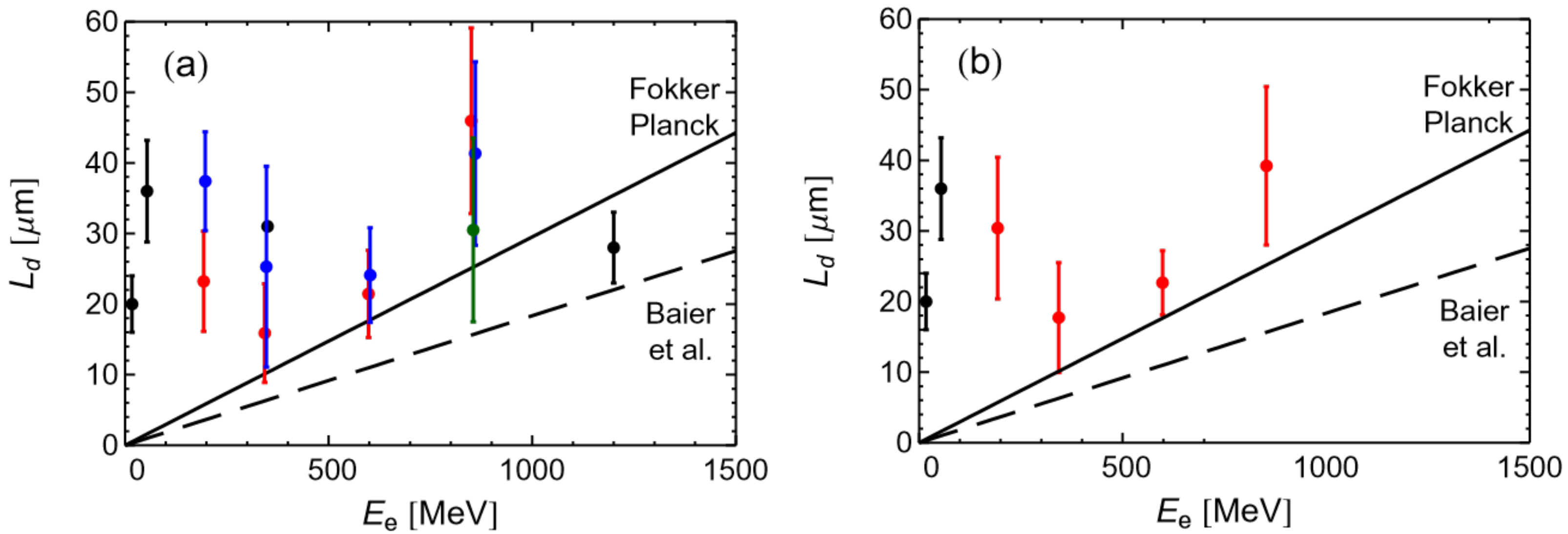


Fig. 7. Dechanneling lengths for (110)-planar channeling of electrons at silicon single crystals as function of the electron beam energy. Left panel (a): experimental values assigned in black are for 17 MeV and 54 MeV the 1/e occupation lengths derived from the 1 ? 0 radiative transition, see Kephart et al. [21]. The point in black at 350 MeV is taken from Komaki et al. [22] for which no error bar has been quoted. The value at 855 MeV in green is a reanalysis of the measurement published in [12, Fig. 15] with allowance for rechanneling. The value at 1200 MeV is taken from [23]. The reanalysis of measurements at MAMI [11] are shown with the red and blue error bars for the measurements at the broad (011) and the narrow (011) structure, respectively, see [11]. The dashed line assigned with ''Baier et al.'' is a calculation of the dechanneling length according to [13, Eq. (10.1)] with U_0 ¼ 22 eV, the dash-dotted line assigned with ''Fokker–Planck'' the result on the basis of the Fokker–Planck equation. Right panel (b): the same as panel (a) with mean values and the measurements in [22,23] omitted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

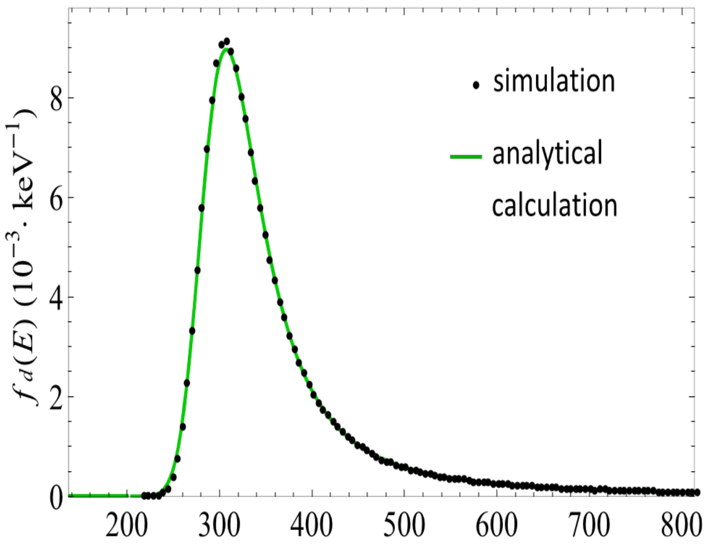
V.M. Biryukov. Phys. Lett. B 765 (2017) 276 – 279

Table 1. The bending radius R, critical angle θ_C, measured dechanneling length L_D, measured inefficiency of volume reflection, and the calculated efficiency, Eq. (1), for the experiments with electrons and negative pions at MAMI, SLAC and CERN.

				E, GeV	R, cm	θ_C, µrad	Measured L_D, µm	Measured 1 – f_{VR}	$R\theta C/L_D$
2014	MAMI	e−	Si (111)	0.855	3.35	217	38	23.3%	19%
2015	SLAC	4[illegible]% e− **	Si (111)	3.35	15	122	55.4	33%	31%
2015	SLAC	e−	Si (111)	4.2	15	109	45.2	27%	34%
2015	SLAC	e−	Si (111)	6.3	15	89	65.3	16%	19%
2015	SLAC	e−	Si (111)	10.5	15	69	57.5	16%	17%
2015	SLAC	e−	Si (111)	14	15	60	55.8	19.3%	
2014	CERN	e−	Si (110)	120	271	19	744*	4.5%	7%
2009	CERN	π−	Si (110)	150	2279	17	930	23.3%	
2009	CERN	π−	Si (111)	150	1292	18	930*	17.26%	25%

S.V. Trofymenko, I.V. Kyryllin. On the ionization loss spectra of high-energy channeled negatively charged particles. Eur. Phys. J. C 80 (2020) 689

• Authors predict ionization loss distribution and propose experimental research of ionization loss of channeling negative particles



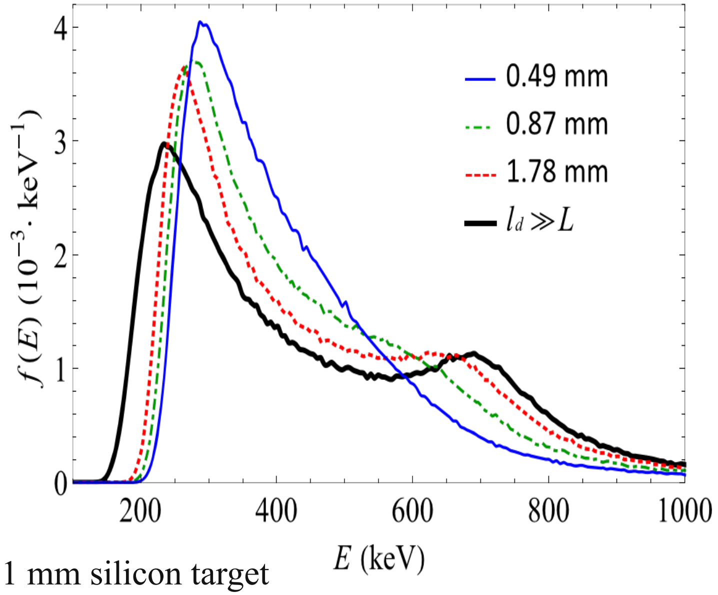
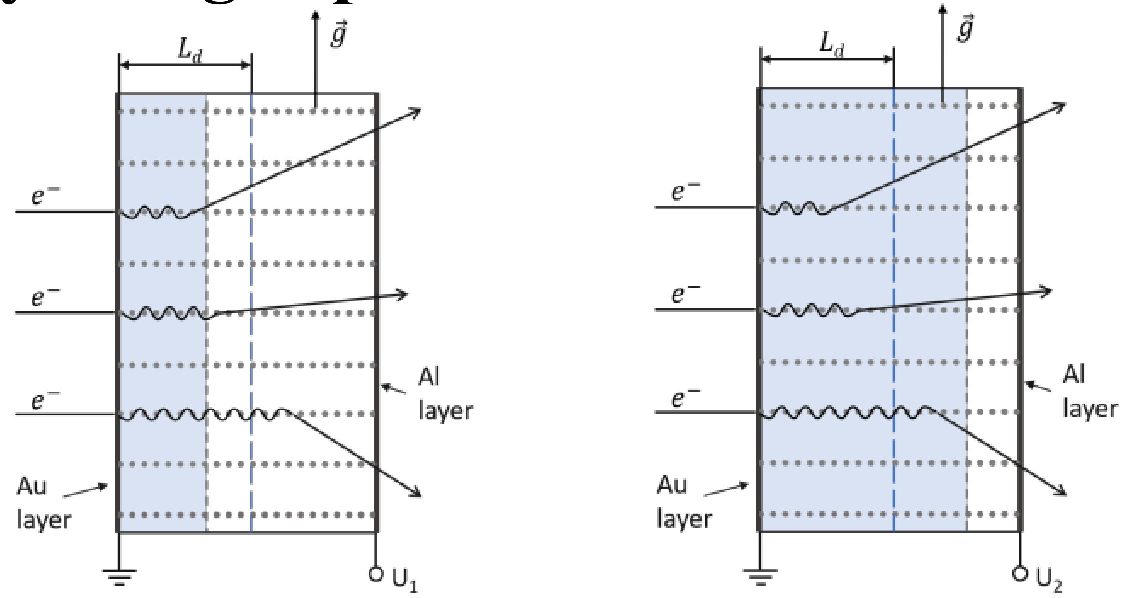


Fig. 1 Ionization loss spectrum of 150 GeV/c π^- mesons in a disoriented 1 mm silicon target

- **Fig. 2** Ionization loss spectra of 150 GeV/c π − mesons in 1 mm silicon target for different values of *ld* (specified in the legend).
- The particles incident along (110) plane

The surface-barrier semiconductor detector with channeling negatively charged particles.



$$d = \sqrt{\frac{2\varepsilon\varepsilon_0}{eN}\left(U + U_K\right)}$$

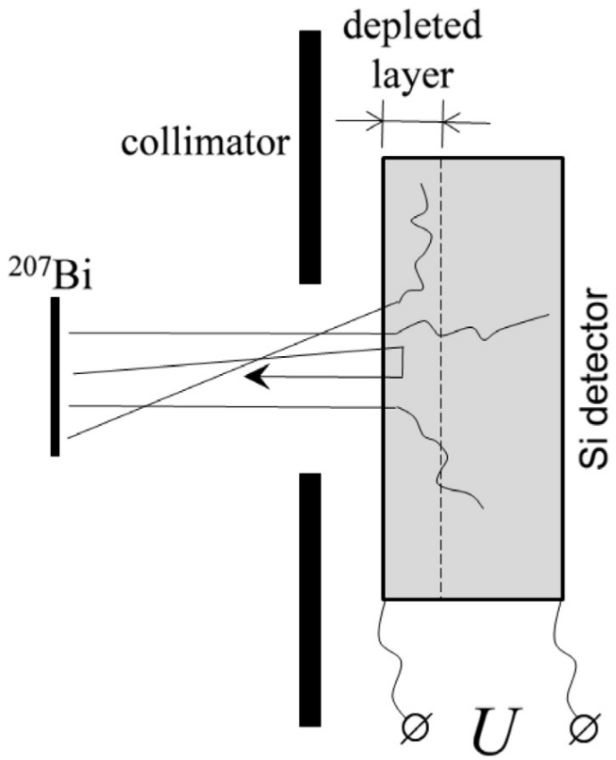
Fig. 1. The surface-barrier semiconductor detector with channeling negatively charged particles. The depleted layer is shown by gray color. The thickness of the depleted layer may be less (in left panel) or more (in right panel) than the dechanneling length L_d depending of the value of the bias voltage U. The incident particles are channeling around of the crystallographic planes of the crystal which are shown by dotted lines and denoted by the reciprocal lattice vector $\vec{g}$. The first and second overhead electrons are dechanneling within the dechanneling length. The third electron is dechanneling outside of the dechanneling length.

Research of the semiconductor detectors with smoothly tunable thickness of the depleted layer

- We began experiments with detectors beginning from radioactive source 207Bi of 0.975 MeV electrons.
- A.V. Shchagin, N.F. Shul’ga, S.V. Trofymenko, R.M. Nazhmudinov, A.S. Kubankin, Semiconductor detector with smoothly tunable effective thickness for the study of ionization loss by moderately relativistic electrons. Nucl. Instrum. Meth. Phys. Res. B 387 (2016) 29–33.

Table 1 Energies and intensities of monochromatic X-ray radiation and electrons with energy up to about 1 MeV emitted by 207Bi radioactive source. Data are taken from [24].
Radiation Energy (keV) Intensity (%)

X-rays Pb Ka2 72.803 21.7
X-rays Pb Ka1 74.969 36.5
e– 481.6935 1.537
e– 553.8372 0.442
e– 975.651 7.08
e– 1047.795 1.84



Research of the semiconductor detectors with smoothly tunable thickness of the depleted layer

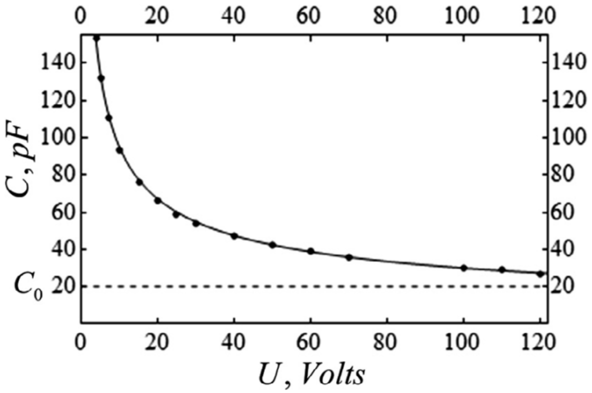


Fig. 2. The dependence of the measured detector capacitance C on the applied voltage U. Experimental data are shown by the points, the results of calculations with the use of formulae (1,2) are presented by the solid line. The dashed line represents the constant value of the circuit capacitance C0.

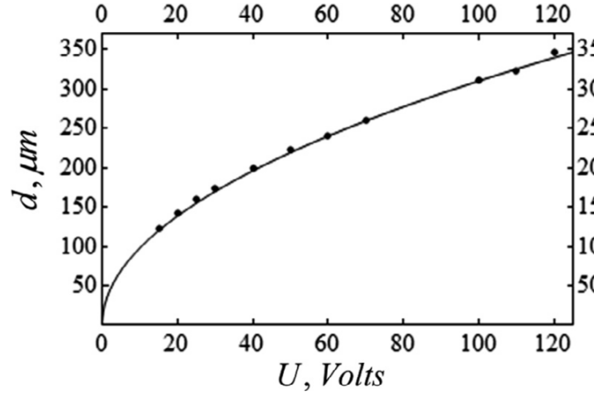


Fig. 3. The dependence of thickness d of the depleted layer of the Si detector on the applied voltage U. Experimental data are shown by the points, results of calculations with the use of formulae (2,3) are shown by the solid line.

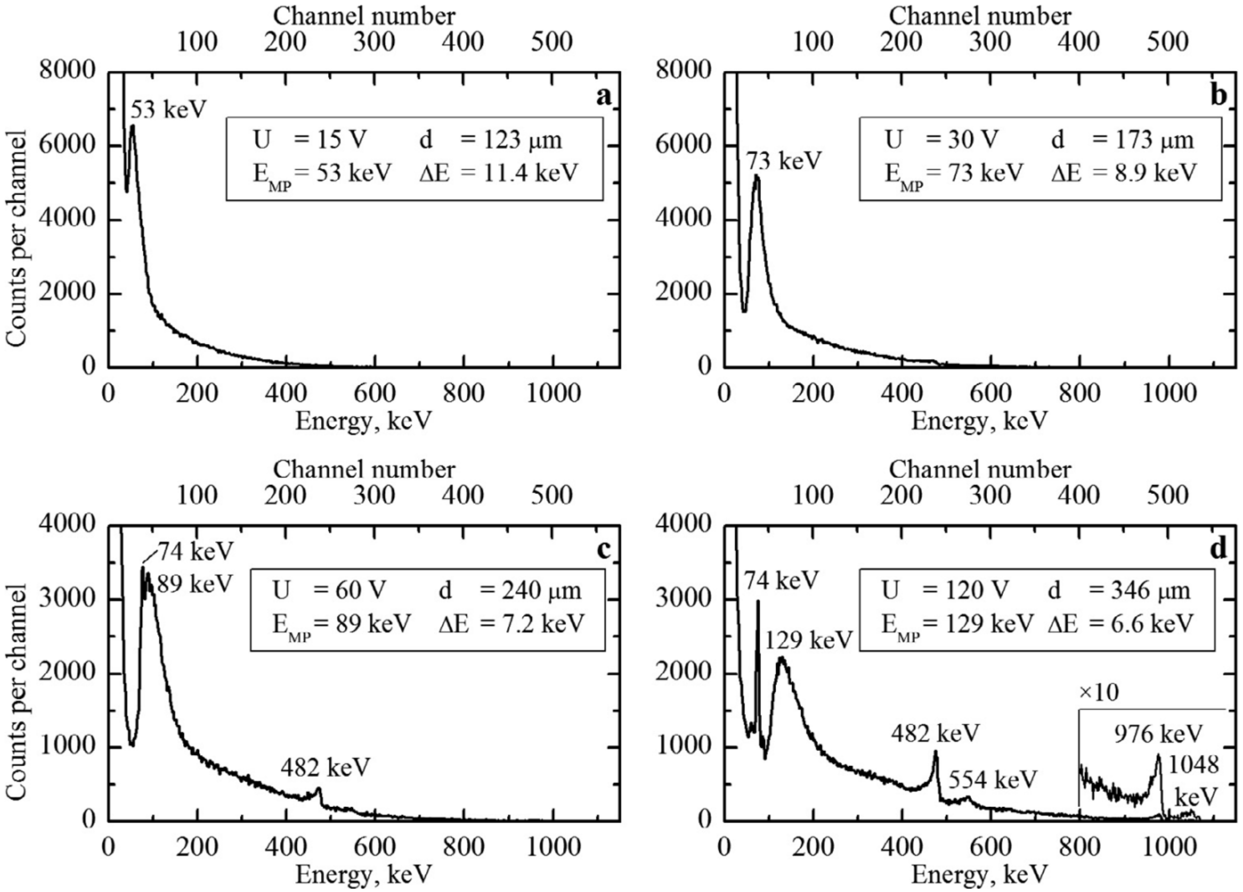
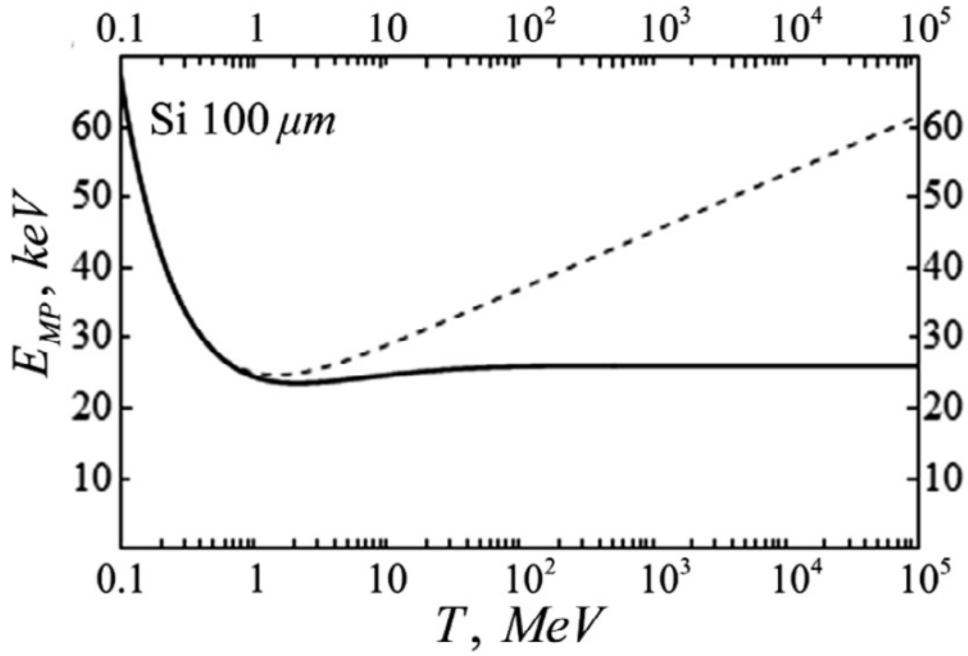
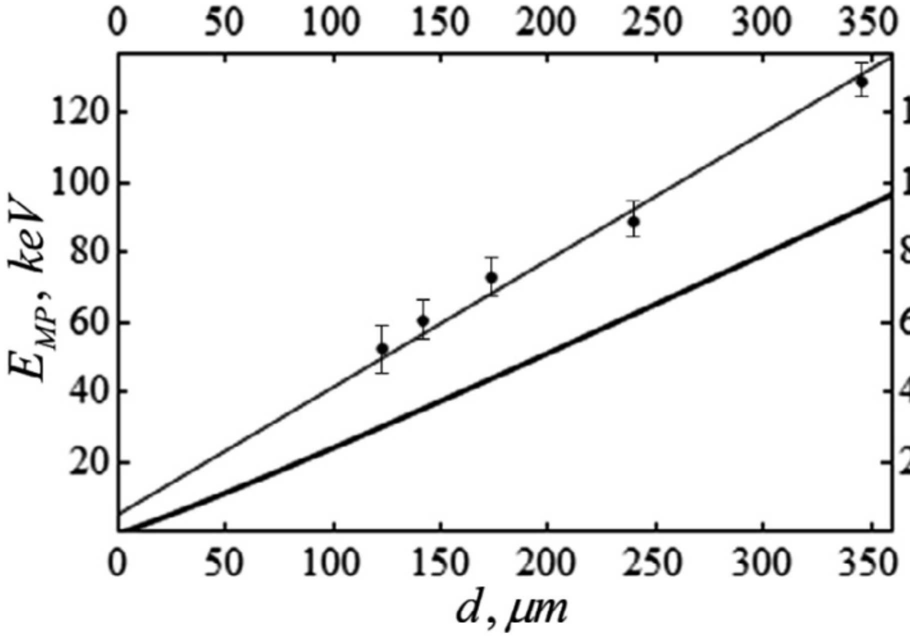


Fig. 4. Spectra of radiation from 207Bi source measured by Si detector with the depleted layer thicknesses 123 lm (a), 173 lm (b), 240 lm (c) 346 lm (d). The values of voltage U, thickness of the depleted layer d, most probable ionization loss EMP, and the spectrometer energy resolution DE are presented for each spectrum.

Most probable ionization loss of electrons MPEL in the silicon detector of thickness 100 lm. Solid line – calculation with the account for density effect, dashed line – calculation without taking the density effect into account.

The most probable ionization loss of electrons with the energy T = 0.976 MeV in the detector for different values of its thickness d. The points represent the measurement results. Upper solid (thin) line – approximation of experimental results with the use of the least square method, lower solid (thick) line – calculation on the basis of (4–6).





Next experiment was performed at 50 GeV proton beam in Protvino

R.M. Nazhmudinov, A.S. Kubankin, A.V. Shchagin, N.F. Shul'ga, S.V. Trofymenko, G.I. Britvich, A.A. Durum, M.Yu. Kostin, V.A. Maisheev, Yu.A. Chesnokov, A.A. Yanovich Study of 50 GeV proton ionization loss by semiconductor detector with smoothly tunable thickness Nucl. Instrum. Meth. Phys. Res. B 391 (2017) 69–72.

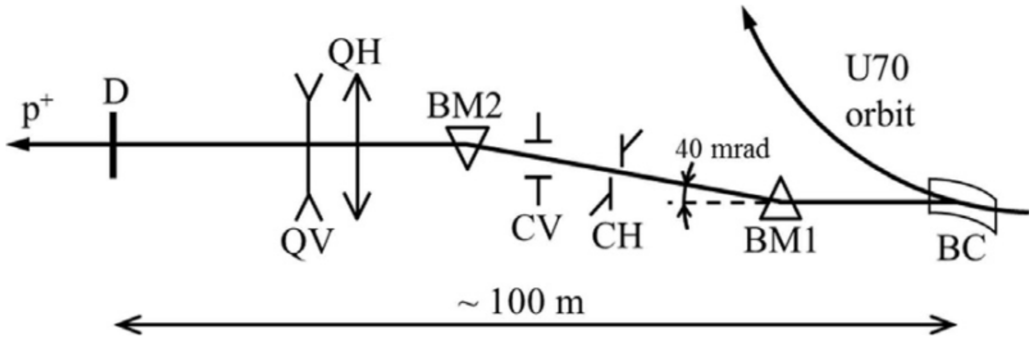


Fig. 1. The beamline and the experimental layout.

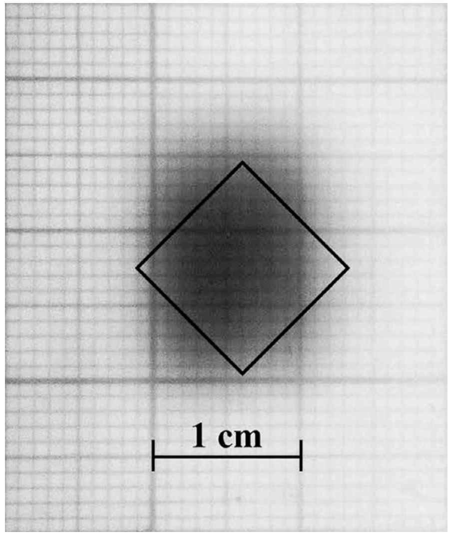


Fig. 2. A proton-beam profile measured by the dosimetry film EBT3. The black box indicates the Si-detector dimension.

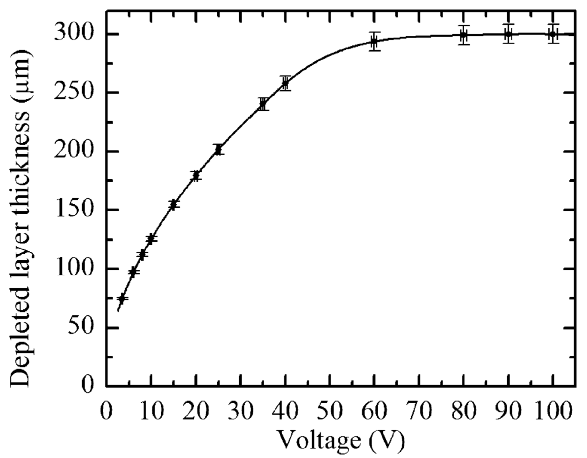


Fig. 3. The thickness of the depleted layer of the detector as a function of the supplied voltage. Results of measurements are shown by points. A cubic spline interpolation is shown by a solid curve.

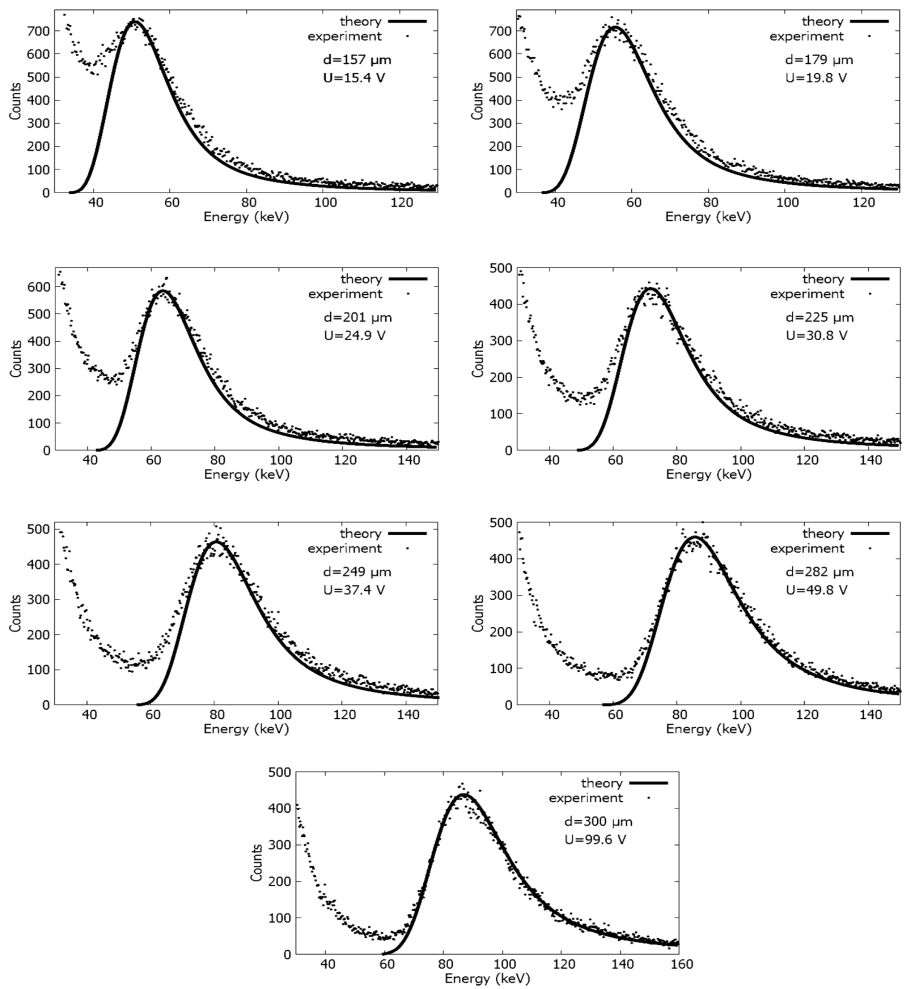


Fig. 4. Spectra of the ionization loss of 50-GeV protons in Si layers of different thicknesses. The measured spectra are shown by dots and the calculated ones by smooth lines.
The thickness d of the depleted layer and voltage supply U are presented on each spectrum.

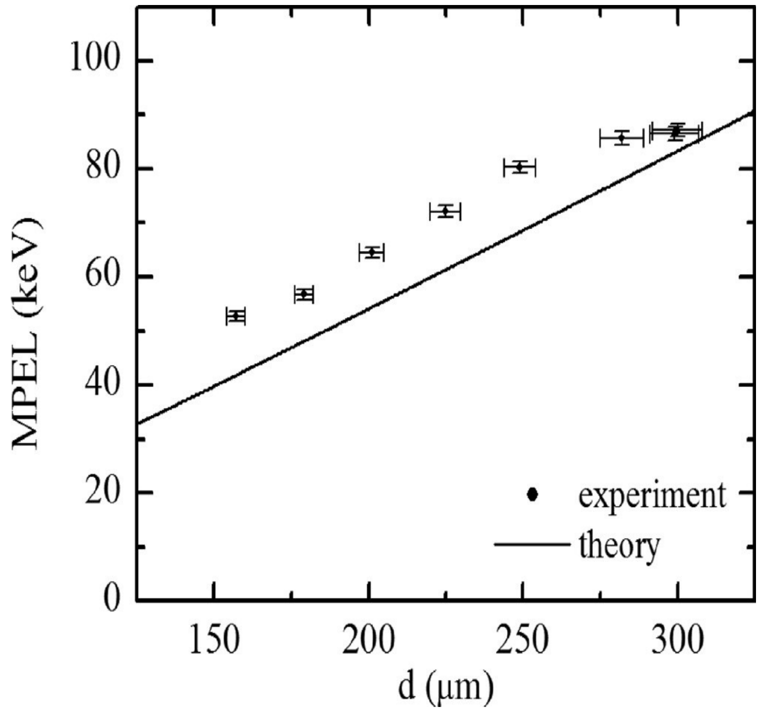
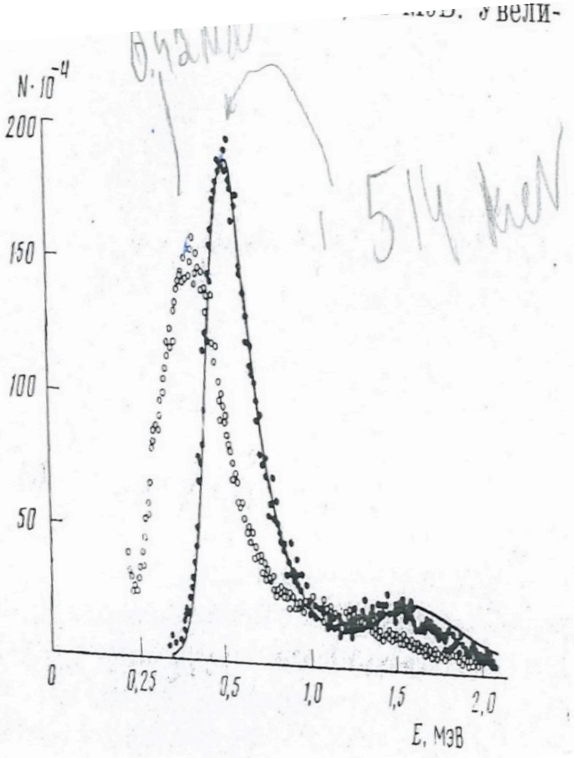


Fig. 5. Dependence of MPEL on the depleted layer thickness d. Solid line –
theoretical calculation; dots – results of measurements.

Experiments in Kharkov. Ionization loss of positrons and electrons

Рис. 1. Ионизационные потери позитронов с энергией 1200 МэВ в монокристалле кремния толщиной 0,16 см. Точки: ● – разориентированный кристалл, ○ – кристалл ориентирован осью [111] вдоль пучка позитронов. Кривая – расчет с учетом наложений и энергетического разрешения детектора



е ширины распределения ...

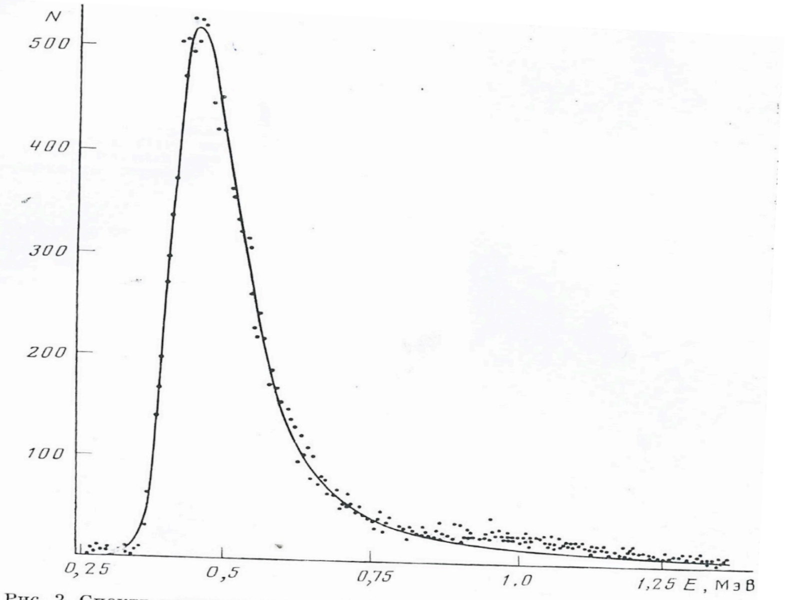


Рис. 2. Спектр ионизационных потерь энергии электронов в монокриста ле кремния. Точки — эксперимент, кривая — расчет с учетом энергетич ского разрешения

Discussion

Let us discuss peculiarities of the proposed method.

1. It seems that the ionization loss is rather convenient for the study of the dechanneling because the most probable energy loss (energy of the Landau peak) is practically independent for electron energies above 1 MeV due to the Fermi density effect, at least for nonchanneling particles (see, e.g., Fig. 6 in [23]). Therefore, the method can be applied at any incident electron beam energy exceeding 1 MeV. A similar situation is valid for other relativistic charged particles.

2. Ionization loss spectra in the channeling regime should contain two spectral peaks. The first peak is the same Landau peak which is produced by nonchanneling particles. The second peak with reduced energy can be associated with the channeling positively charged particles, as it was observed for positrons [5] and protons [6-9]. In the case of an incident beam of negatively charged particles, one can expect the appearance of a second smoothed peak with increased energy relative to the Landau peak, as it was theoretically predicted in [21] and shown in Fig. 2 [21]. Thus, the contributions of channeling and nonchanneling fractions of the incident beam of electrons or positrons can be distinguished.

3. The results of measurements of ionization loss spectra should be independent on the emission or non-emission of channeling radiation by some parts of the relativistic channeling particles. This is because the emission of channeling radiation leads to a reduction of the particle energy only, but the particle remains in the channeling regime. The ionization loss should not be changed due to the Fermi density effect (see item 1).

4. The ionization loss should be the same for particles channeling from the beginning of their motion in the crystal or rechanneling inside the crystal. This peculiarity can help to clear up the role of rechanneling of particles in the crystal.

5. The measurement of the ionization loss in different thicknesses of the depleted layer can be performed in only one immovable detector-target with preliminary fixed alignment.

6. The spectrum of ionization loss measured at only one fixed bias voltage and depleted layer thickness can give information about channeling and nonchanneling fractions of the beam averaged over the entire path of the particles in the depleted layer. But two spectra measured with two different thicknesses of the depleted layer can provide information about processes in the layer inside of the crystal which is between two edges of the depleted layers. This is a unique possibility to extract information about dechanneling or rechanneling processes in a layer inside the crystal. For example, spectra of ionization loss measured at bias voltages U_2 and U_1 can give the information about processes in the layer between edges of depleted layers d_2 and d_1 of thickness $d_2 - d_1$, see Fig. 1. In other words, it is possible to extract differential by particle path data which can give access to the particle dynamics inside the crystal. The space resolution of this differential measurements can be less than the dechanneling length, especially at high particle energies.

7. A semiconductor detector-target based on different crystalline materials, for instance germanium, can be used in research if the thickness of the depleted layer can be regulated by the bias voltage in such detector.

8. Probably, a bent silicon crystal similar to the one used, e.g., in [18] can serve as a surface-barrier detector for studying the dechanneling length of negatively charged particles and other related phenomena. For instance, ionization loss at volume reflection and volume capture of particles in a bent crystal can be measured and investigated. Note, that similar detectors were installed on the bent Si crystal plates and were successfully used in the first experiments on proton channeling phenomena in [6-8].

9. The detector-target can be placed in the beam with its front surface as shown in Fig. 1. In this case one can observe ionization loss of particles starting their motion in the crystal. Also, the detector-target can be placed in the beam with its rear surface. In this case one can observe the ionization loss of particles finalizing their motion in the crystal. Such installation can be useful for research of rechanneling phenomena.

Preparation to the experiment. Measurement of the depleted layer thickness.

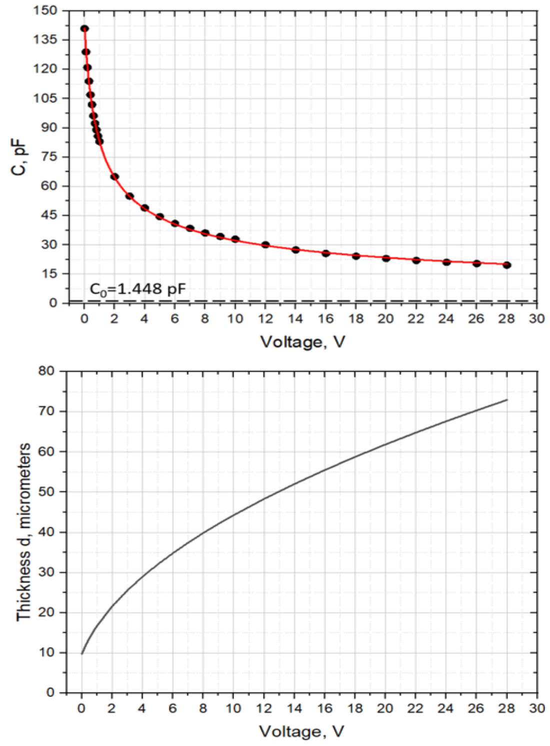


Fig. 1. Capacitance and thickness for detector S1223-1.

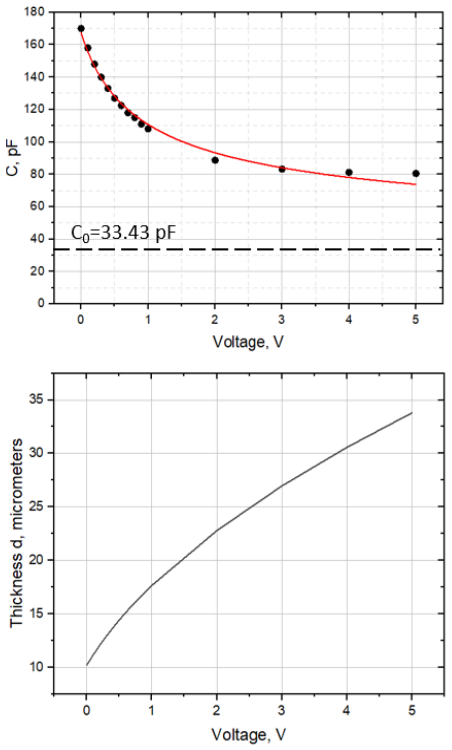


Fig. 2. Data for diode S1226-5

In measurements, we used the Capacitance Meter: Boonton Electronics Model 72B.

Experimental data were approximated by the method of least squares for every of two detectors by the formula

$$C(U) = \sqrt{\frac{\varepsilon\varepsilon_0 eN}{2}}\frac{S}{\sqrt{U+U_K}} + C_o \qquad (1)$$

where C(U) is measured capacitance, $\varepsilon = 11.9$ is the dielectric permittivity of the Si crystal, $\varepsilon_0 = 8.85 \cdot 10^{-12}\ \frac{F}{m}$ the dielectric permittivity of free space, $e = 1.6\ 10^{-19}$ C is the electron charge, N the density of acceptors or donors in units m^{-3}, U is the bias voltage, and $U_K \approx 0.5$ Volts for a silicon detector, S is the square of the detector: $S_{S1223\text{-}1}=3.6*3.6*10^{-6}\ m^2$, $S_{S1226\text{-}5}=2.4*2.4*10^{-6}\ m^2$, C_0 is the parasitic capacitance.

Then, values N and C_0 for every detector were determined.

Graphics of measured points and calculated by (1) capacitance C(U) are in Figs. The level C_0 is noted.

New graphics d(U) (the thickness of the depleted layer as a function of the voltage) calculated by the formula

$$d = \sqrt{\frac{2\varepsilon\varepsilon_0}{eN}} * \sqrt{U+U_K} \qquad (2)$$

One can see from Figs. 1,2, that calculations coincide to experimental data for diode S1223-1 VERY good, but for diode S1226-5 – not very well. The desirable thickness about 30 micrometers is at 4 Volts in S1223-1. It seems is OK for our plans.

Conclusion

In this work we propose a new method for further experimental studies of dechanneling phenomena and to obtain differential information about dynamics of the particle in crystal. The peculiarities of the proposed here and in [21] experimental research methods would allow to clarify the situation with the dechanneling length of electrons. A better understanding of the dechanneling length properties can be useful in the production of positrons [33,34] and other particles such as neutrons by an electron beam in crystals, and in the development of crystalline undulators (see, e.g., [35]), and at a crystal-based extraction of electron beams from a synchrotron [36].

Acknowledgments

The authors are thankful to H. Backe, S.V. Trofymenko, and I.V. Kyryllin for useful discussions. A.V. Shchagin is grateful to DESY Hamburg (Germany) and Helmholtz Association (HGF) for granted asylum after fleeing the war in Ukraine, outstanding support and provided funding from the Initiative and Networking Fund under the contract number GI-022. This project has received funding through the MSCA4Ukraine project, which is funded by the European Union.