ПРО ВІДХИЛЕННЯ ШВИДКИХ ЗАРЯДЖЕНИХ ЧАСТИНОК ЗІГНУТИМИ КРИСТАЛАМИ

І.В. Кириллін, М.Ф. Шульга

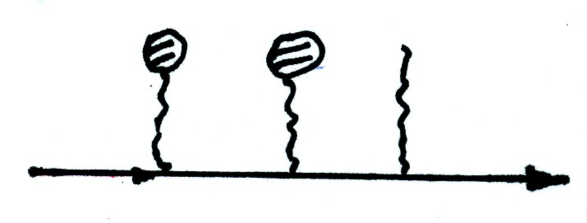
ІТФ ім. О.І. Ахієзера, ННЦ ХФТІ

Семінар, присвячений пам’яті Петра Івановича Фоміна
«КВАНТОВА ТЕОРІЯ ПОЛЯ ТА КОСМОЛОГІЯ»
5 липня 2022 р.

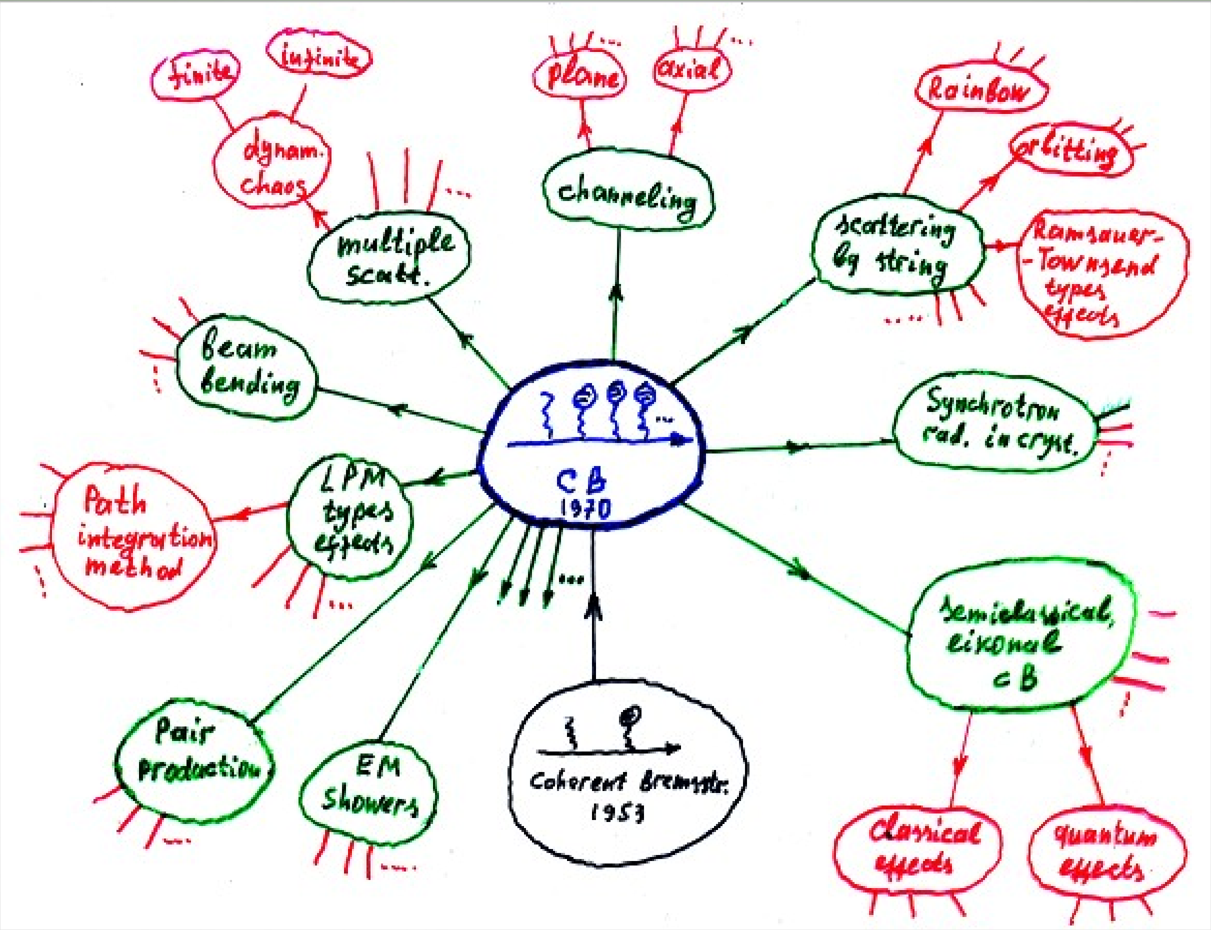
А.И. Ахиезер, П.И. Фомин, Н.Ф. Шульга

Когерентное тормозное излучение электронов и позитронов ультрарелятивистской энергии в кристаллах

Письма ЖЭТФ, 1971, Т. 13, с. 713-715

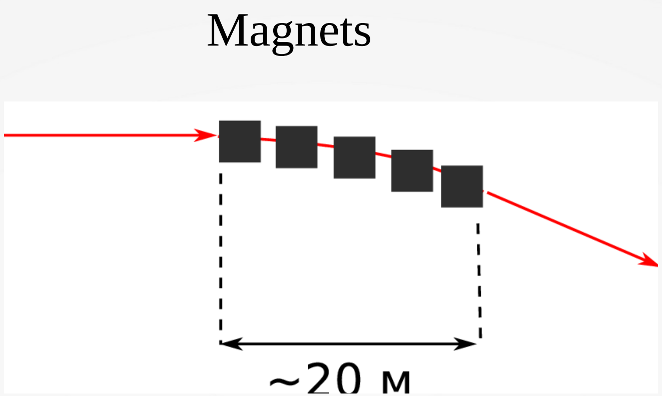


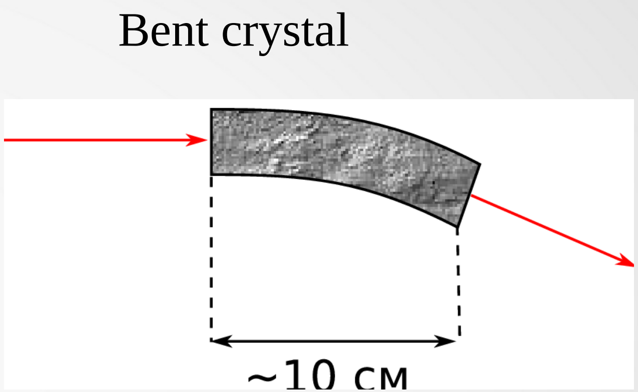
Проблемы, порожденные теорией когерентного излучения в кристаллах



Bent crystals and magnetic deflection systems

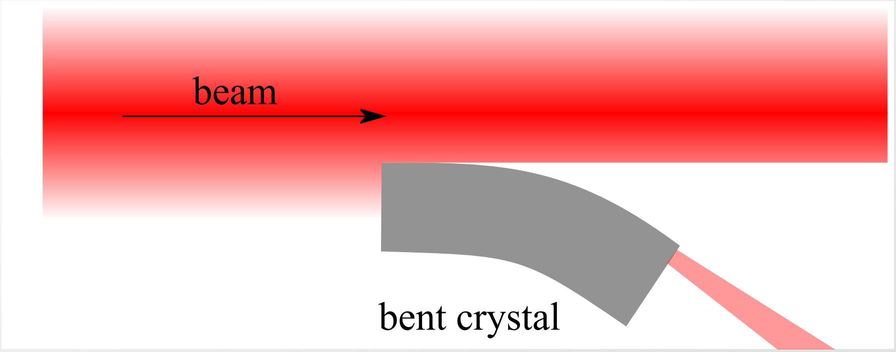
$E_{str} \sim 10^{10}$ V/cm
$E_{pl} \sim 10^{9}$ V/cm





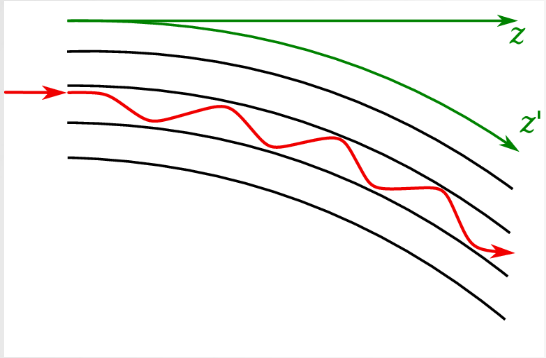
Advantages of bent crystals in comparison with magnetic deflection systems:

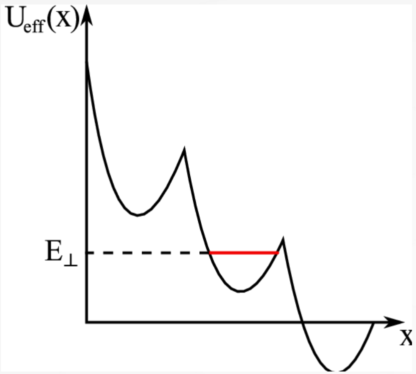
- Small size
- do not need electricity consumption
- do not need cooling



Planar channeling

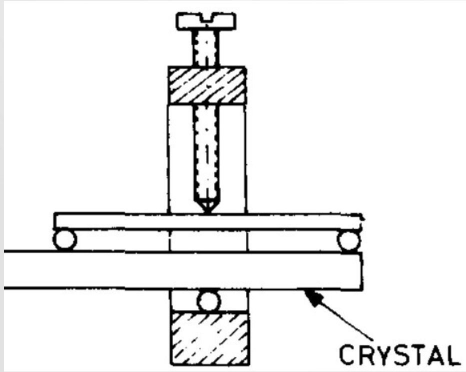
Tsyganov E. N. Fermilab TM-682, TM-684. 1976.

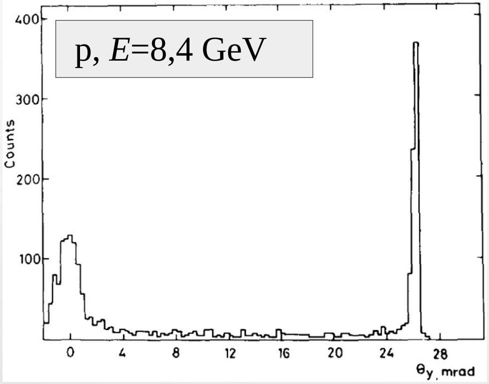




Таратин А. М., Цыганов Э. Н., Воробьев С. А. Поворот пучков заряженных частиц изогнутым монокристаллом. Численный эксперимент. Письма в ЖТФ. 1978. Т. 4. С. 947–950.
Tarantin A. M., Tsyganov E. N., Vorobiev S. A. Computer simulation of deflection effects for relativistic charged particles in a curved crystal. Phys.Lett. A. 1979. Vol. 72, No. 2. P. 145–146.

p, *E*=1 GeV, a) *R*=0,29 cm, b) *R*=0,112 cm





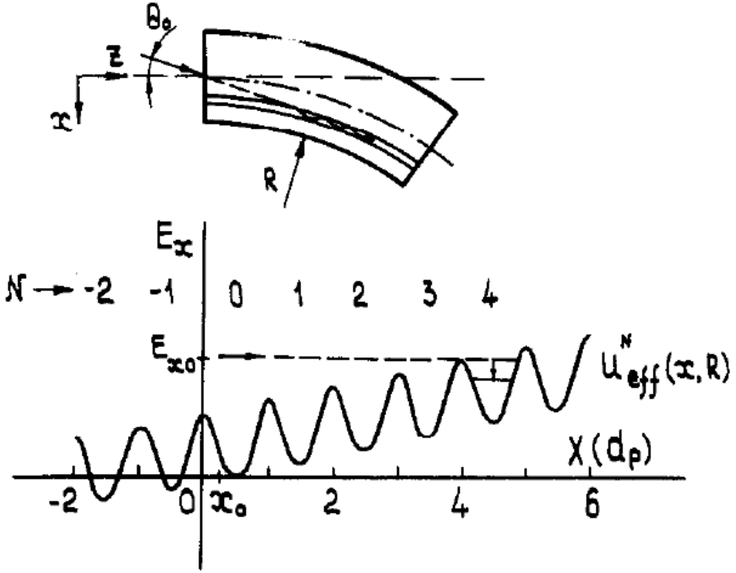
Elishev A. F., Filatova N. A., Golovatyuk V. M. et al. (I.A. Grishaev, G.D. Kovalenko, B.I. Shramenko) Steering of charged particle trajectories by a bent crystal. Phys. Lett. B. 1979. Vol. 88, No. 3-4. P. 387–391.

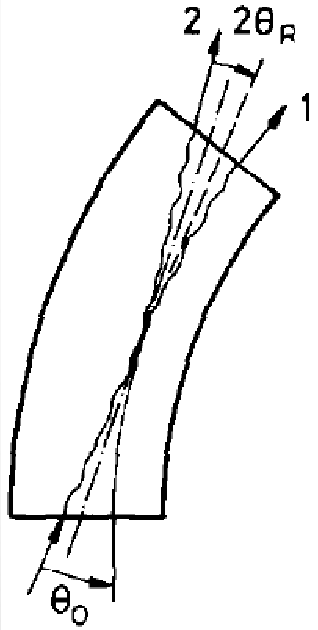
Volume reflection

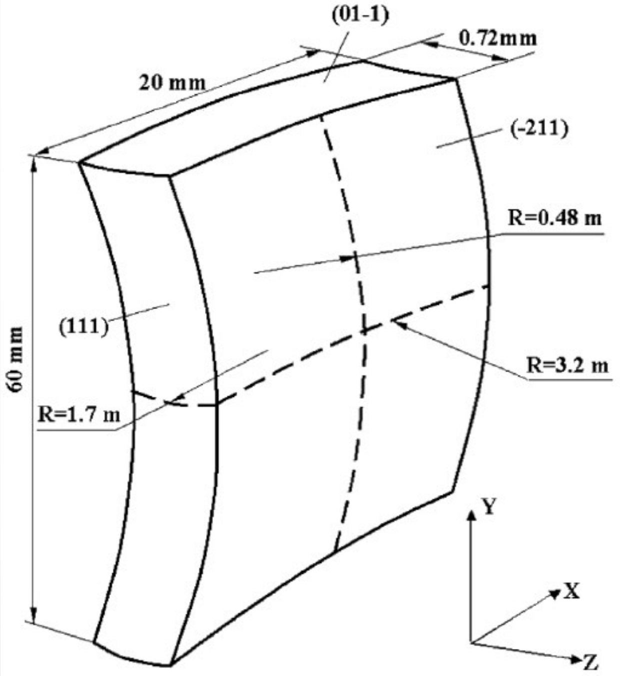
Taratin A. M., Vorobiev S. A. Phys. Lett. A. 1986. Vol. 115, No. 8. P. 398–400.
Taratin A. M., Vorobiev S. A. Nucl. Instrum. Meth. B. 1987. Vol. 26, No. 4. P. 512–521.
Taratin A. M., Vorobiev S. A. Phys. Lett. A. 1987. Vol. 119, No. 8. P. 425–428.

$$U_{eff}(x,R) = U(x) + pv\frac{x}{R}$$

$$E_x = \frac{pv\theta_x^2}{2} + U_{eff}(x,R)$$

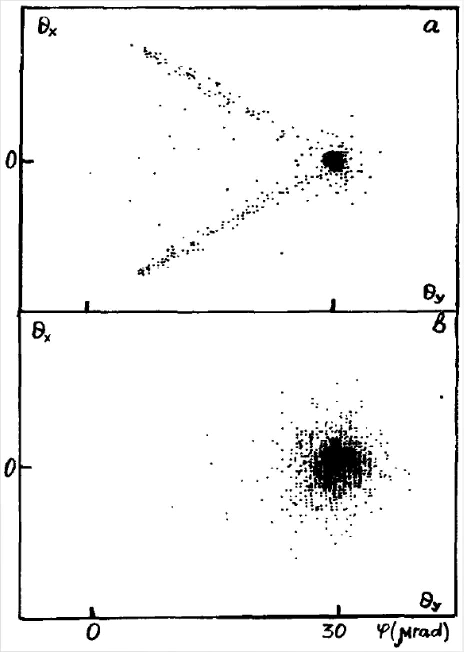






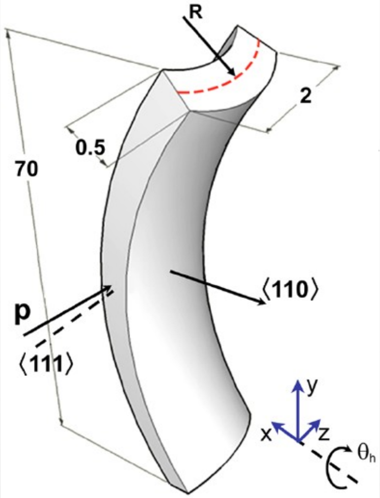
Stochastic deflection

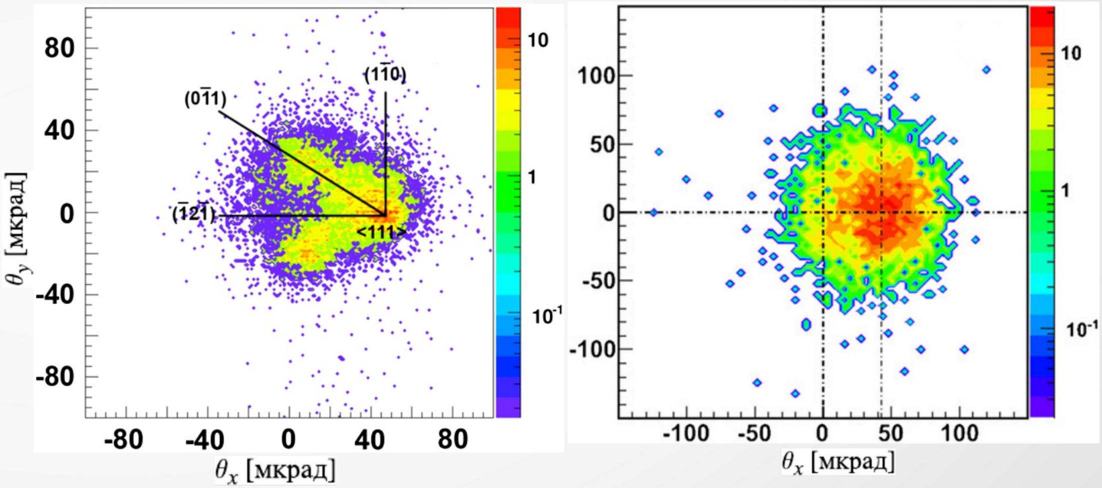
Grinenko A. A., Shul'ga N. F. J. Exp. Theor. Phys. Lett. 1991. Vol. 54. P. 524–528.
Greenenko A. A., Shul'ga N. F. Nucl. Instrum. Meth. B. 1994. Vol. 90, No. 1-4. P. 179–182.
Shul'ga N. F., Greenenko A. A. Phys. Lett. B. 1995. Vol. 353, No. 2. P. 373–377.



E=10 TeV

$$\langle\psi^2\rangle = \frac{lL}{R^2} \le \psi_c^2$$



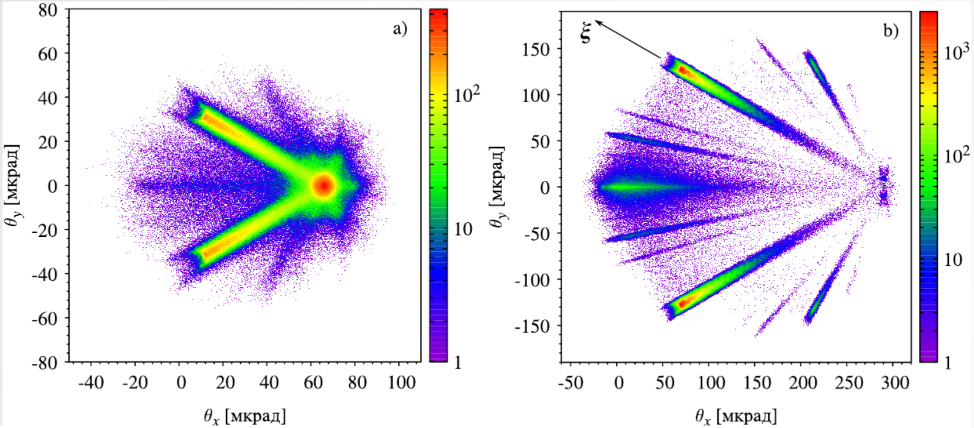


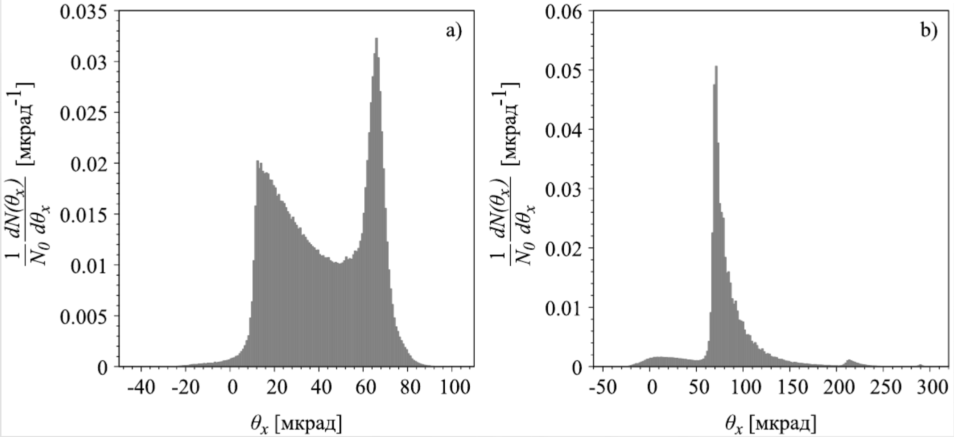
Scandale W., Vomiero A., Baricordi S. et al. High-efficiency deflection of high-energy protons through axial channeling in a bent crystal. Phys. Rev. Lett. 2008. Vol. 101, No. 16. P. 164801.
Scandale W., Vomiero A., Bagli E. et al. High-efficiency deflection of high-energy negative particles through axial channeling in a bent crystal. Phys. Lett. B. 2009. Vol. 680, No. 4. P. 301–304.

Changing the shape of the beam

R=30,3 m

R=6,9 m

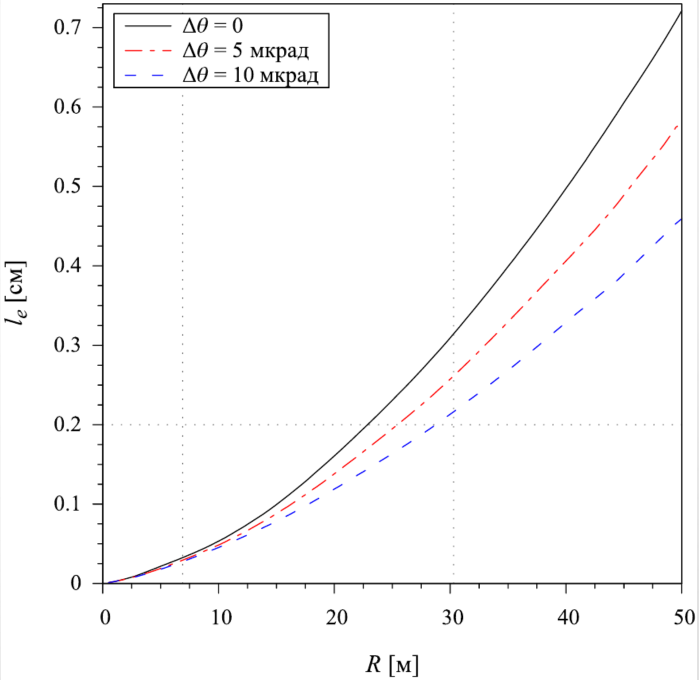




p, E=400 GeV, Si <111>, L=2 mm

$|\varphi_{pl}| = \pi/6 \rightarrow R_{cr} \approx 35$ см

$$\frac{dN}{dl} = -CN \rightarrow N_{pl}(l) = N_0\left(1 - e^{-l/l_e}\right)$$

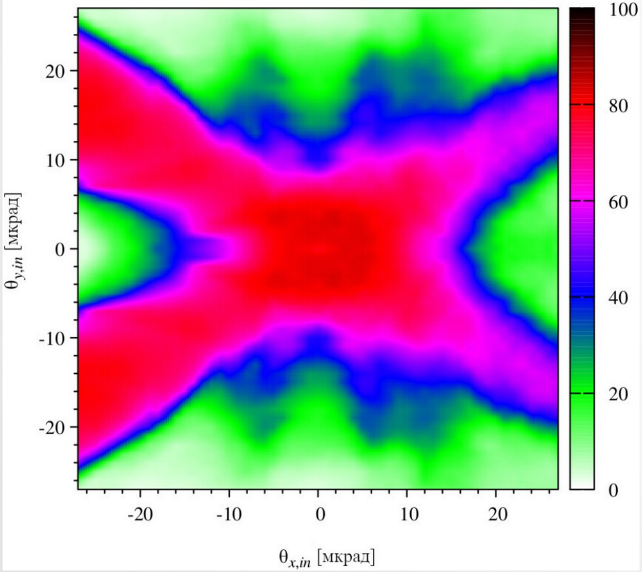


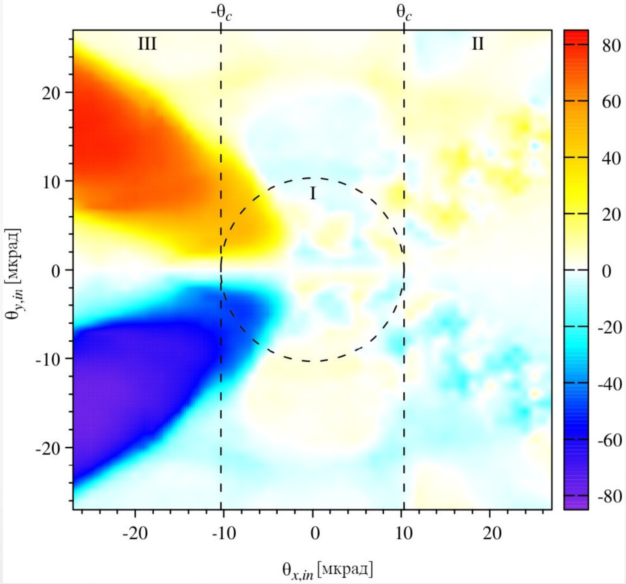
Changing the shape of the beam

p, E=400 GeV, Si <111>, L=2 mm, R=6,9 m

$$\frac{N_{(0\bar{1}1)} + N_{(\bar{1}01)}}{N_0}$$

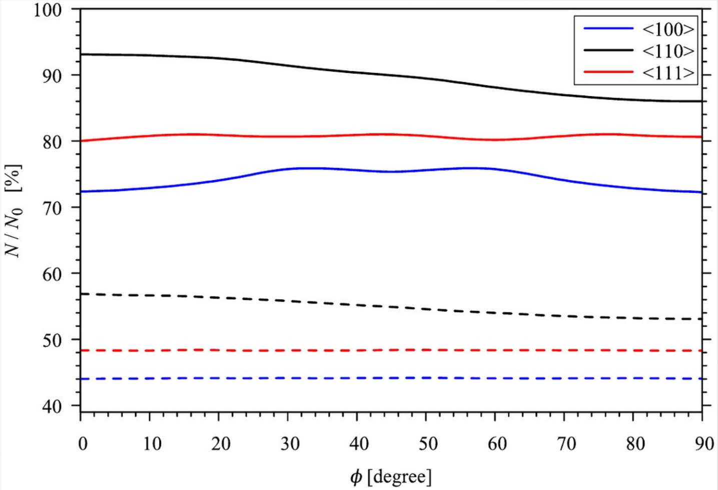
$$\frac{N_{(0\bar{1}1)} - N_{(\bar{1}01)}}{N_0}$$





$$\alpha_{st} = \frac{L_{st}}{R} = \frac{\psi_m^2}{l/R + \xi R}$$

$$\left(\psi_c^{\langle 110\rangle}/\psi_c^{\langle 111\rangle}\right)^2 \approx 1,25$$



$$(\theta_x - \theta_B)^2 + \theta_y^2 \leq \psi_c^2$$

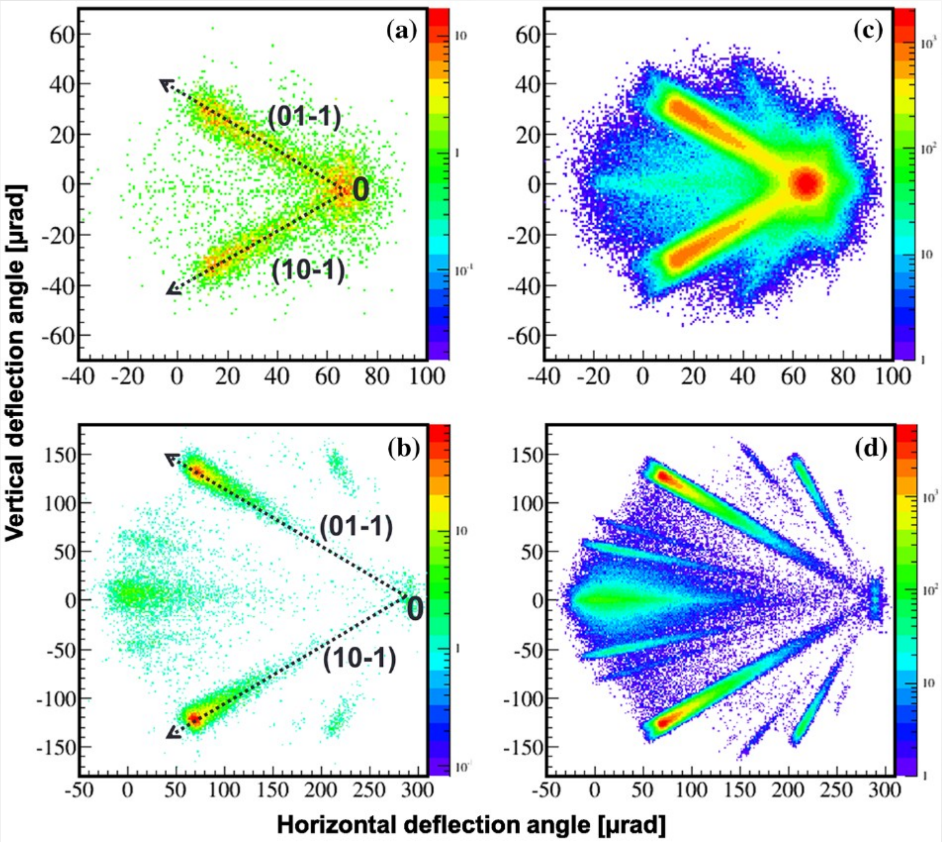
$e^{\pm}$, E=120 GeV, Si, L=2 mm, α=90 μrad

Changing the shape of the beam

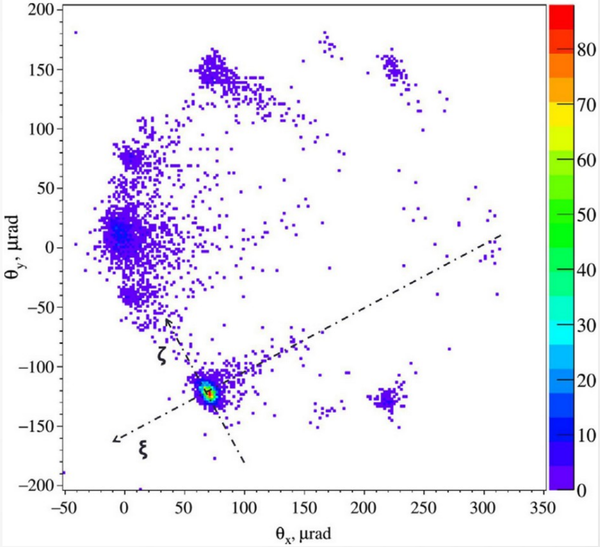
p, *E*=400 GeV, Si <111>, *L*=2 mm

R=30,3 m

R=6,9 m



p, *E*=400 GeV, Si <111>, *L*=2 mm, R=6,9 m, $\theta_{x,in}$=-8 μrad, $\theta_{y,in}$=-4 μrad

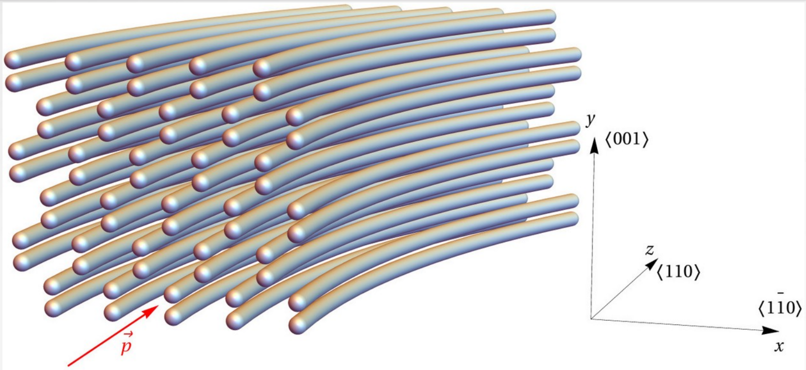


Bandiera L., Mazzolari A., Bagli E. et al. (Kirillin I. V.). Relaxation of axially confined 400 GeV/c protons to planar channeling in a bent crystal. Eur. Phys. J. C. 2016. Vol. 76. P. 80 (1–6).

Bandiera L., Kirillin I. V., Bagli E. et al. Splitting of a high-energy positively-charged particle beam with a bent crystal. Nucl. Instr. Meth. Phys. Res. B. 2017. Vol. 402. P. 296–299.

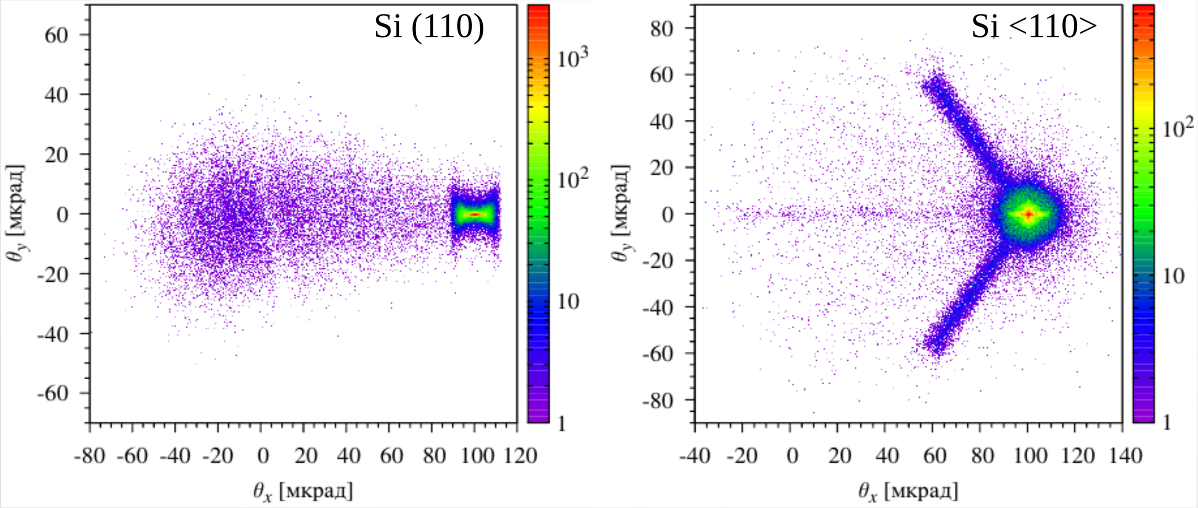
Probability of close collisions

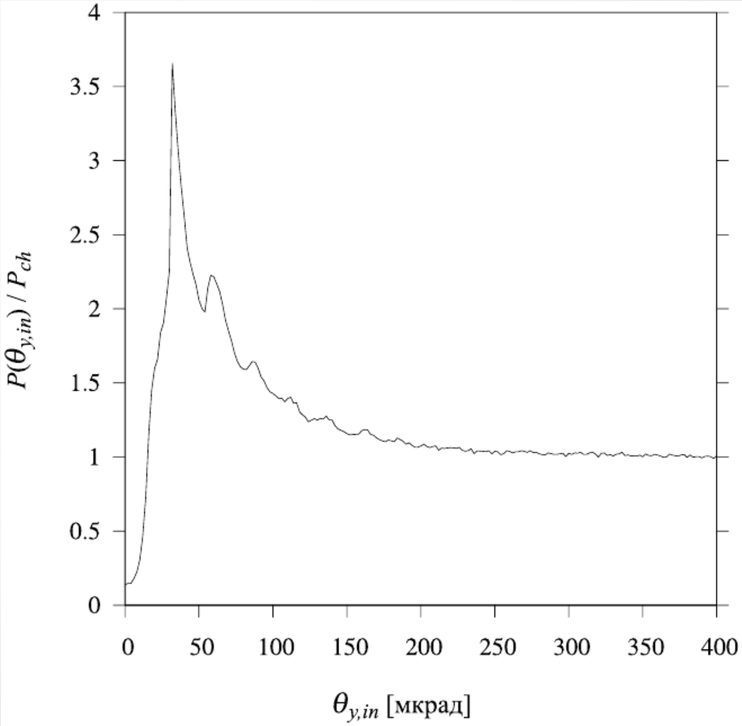
p, *E*=270 GeV,
Si <110>, (110),
L = 5 mm,
R = 5 m



$$w_a = \frac{4\pi r_T^2}{a_x a_y} = 4\sqrt{2}\pi r_T^2/a^2 \approx 3.39 * 10^{-3}$$

$$w_p = \frac{4r_T}{a_x} = 4\sqrt{2}r_T/a \approx 78.12 * 10^{-3}$$

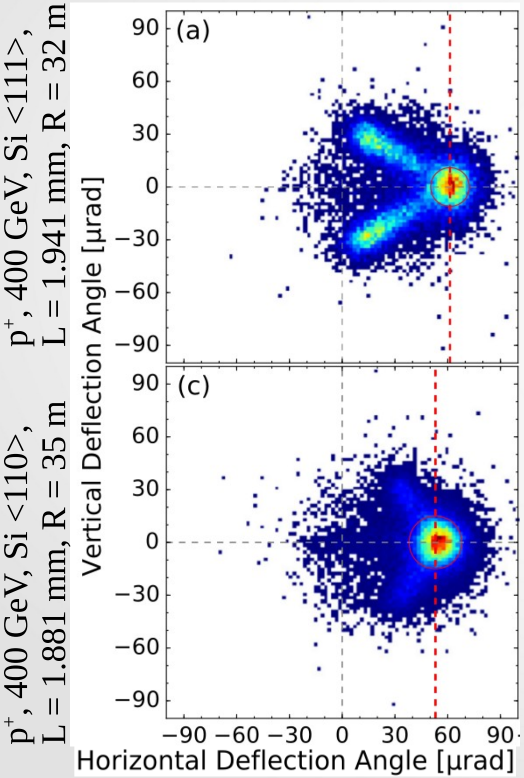




Chesnokov Yu.A., Kirillin I.V., Scandale W. et al. Phys. Lett. B. 2014. Vol. 731. P. 118–121.

Probability of close collisions

Scandale W., Arduini G., Butcher M. et al. Phys. Lett. B. 2016. Vol. 760. P. 826–831.
Scandale W., Andrisani F., Arduini G. et al. Eur. Phys. J. C. 2018. Vol. 78, No. 6. P. 505.



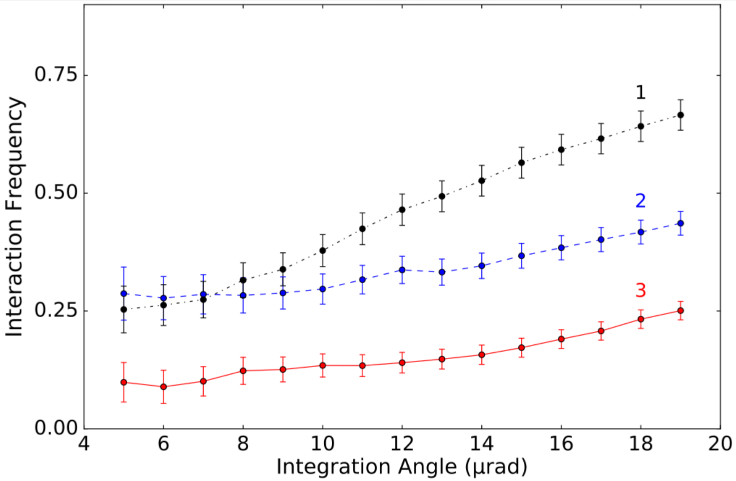
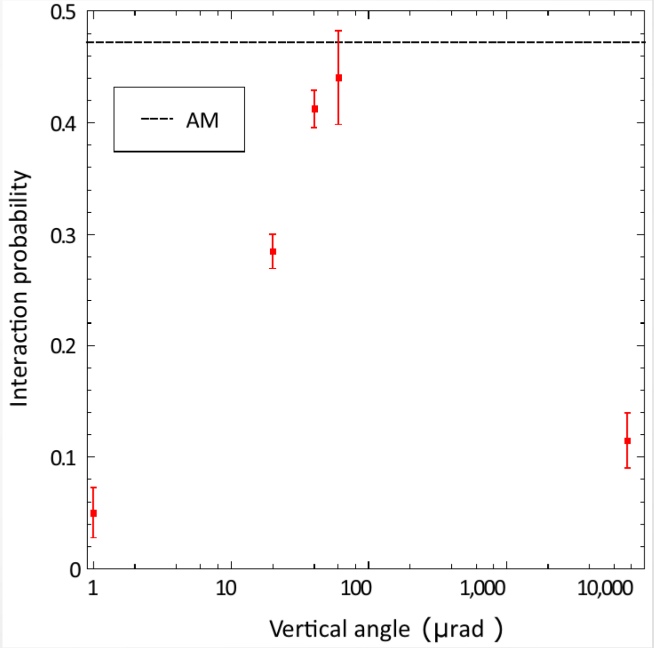
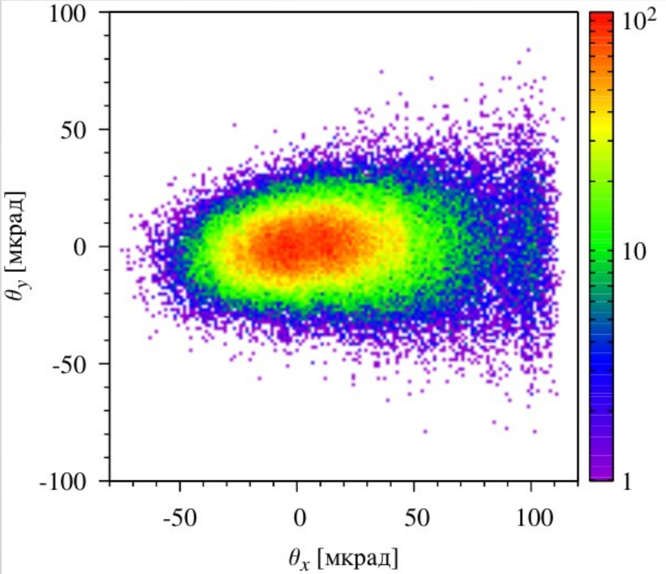


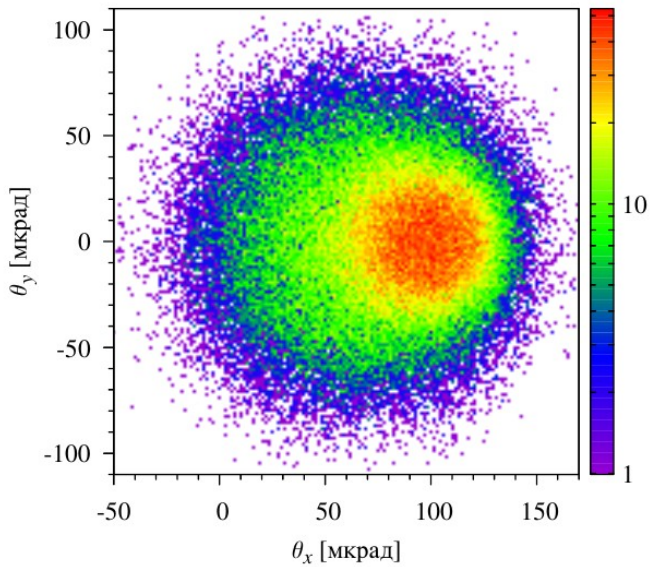
Fig. 5. Measured inelastic nuclear interaction (INI) frequency of 400 GeV/c protons interacting with the ⟨111⟩ and ⟨110⟩ crystals as a function of the angular region around the (110) planar channeling (black dash-dotted line, 1), the ⟨111⟩ axial channeling (blue dashed line, 2) and ⟨110⟩ (red continuous line, 3) orientations. The values are normalized to the INI frequencies for the amorphous crystal orientation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

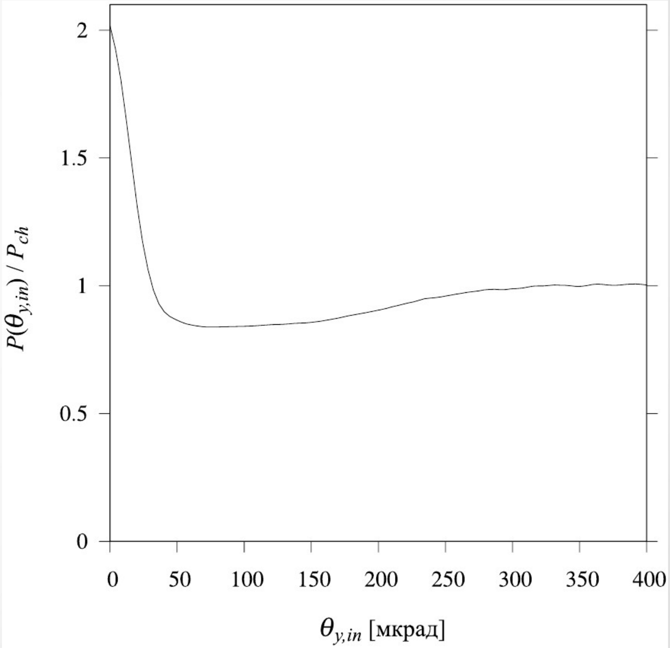


Probability of close collisions

π^{-}, E = 270 ГэВ, Si <110>, L = 5 mm, R = 5 m







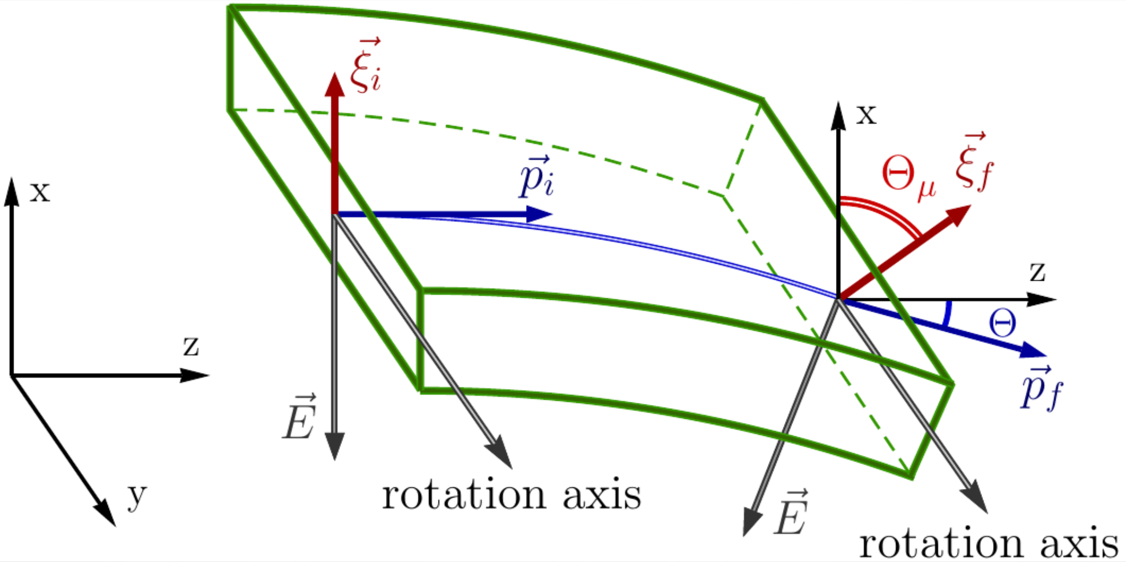
Kirillin I.V., Shul'ga N.F. Nucl. Instr. Meth. Phys. Res. B. 2015. Vol. 355. P. 49–52.

Feasibility of measuring the magnetic dipole moments of the charm baryons at the LHC using bent crystals

Fomin A.S., Korchin A.Yu., Stocchi A. et al. (S.P. Fomin, I.V. Kirillin, N.F. Shul'ga) J. High Energy Phys. 2017. Vol. 2017. № 8. P. 120 (1–26).

$$\Theta_\mu = \gamma\left(\frac{g}{2} - 1 - \frac{g}{2\gamma^2} + \frac{1}{\gamma}\right)\Theta \approx \gamma\left(\frac{g}{2} - 1\right)\Theta$$

(V.G. Baryshevsky, 1979; V.L. Lyuboshits, 1980)



Optimal radius of curvature (stochastic deflection)

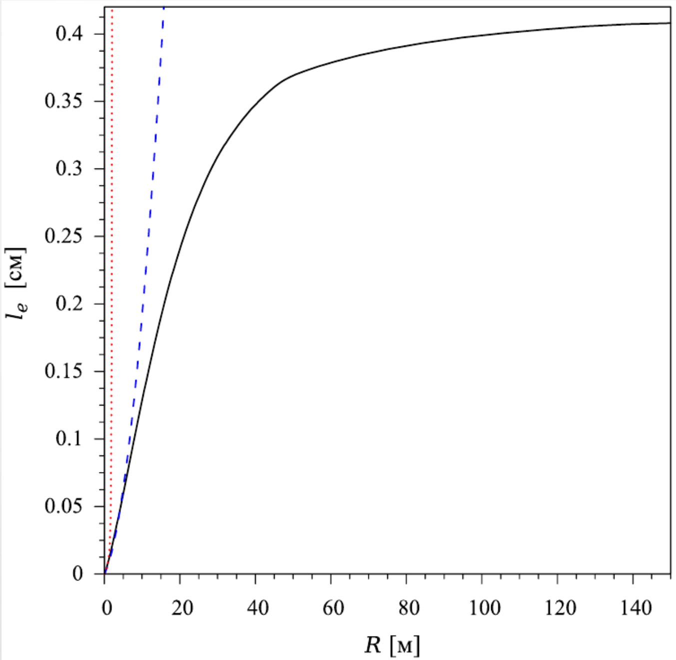
$$\langle\psi^2\rangle = \frac{lL}{R^2} \le \psi_c^2$$

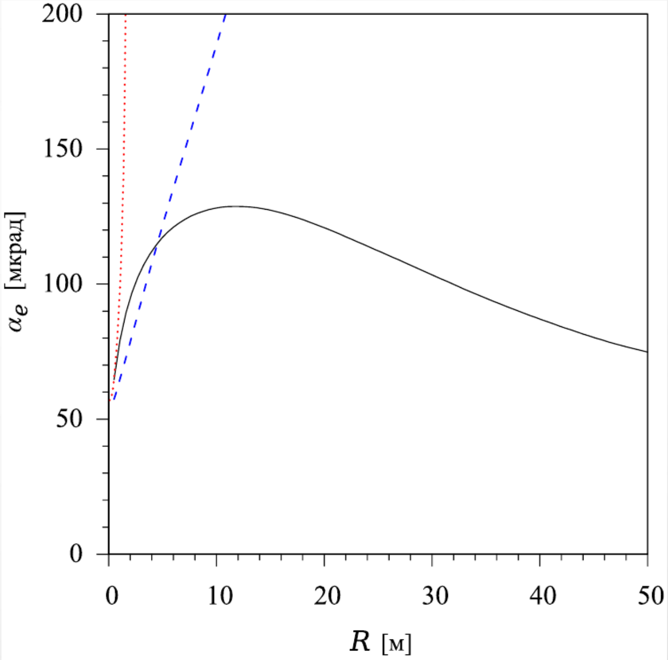
$$\overline{\Psi_{inc}}^2 = \xi L$$

$$L_{st} = \frac{\psi_m^2}{l/R^2 + \xi}$$

$$\alpha_{st} = \frac{L_{st}}{R} = \frac{\psi_m^2}{l/R + \xi R}$$

π^-, E=150 GeV, Si <110>





Kirillin I.V., Shul'ga N.F., Bandiera L. et al. Eur. Phys. J. C. 2017. Vol. 77. P. 117 (1–7).

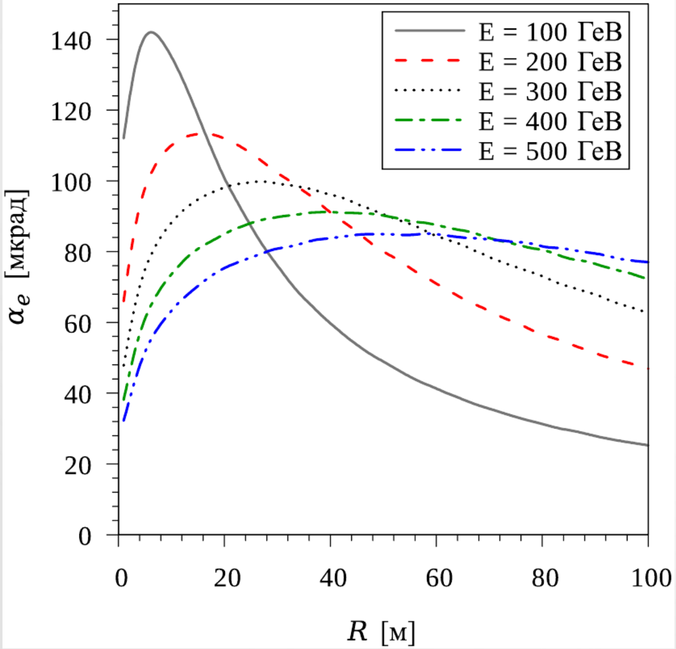
Optimal radius of curvature (stochastic deflection)

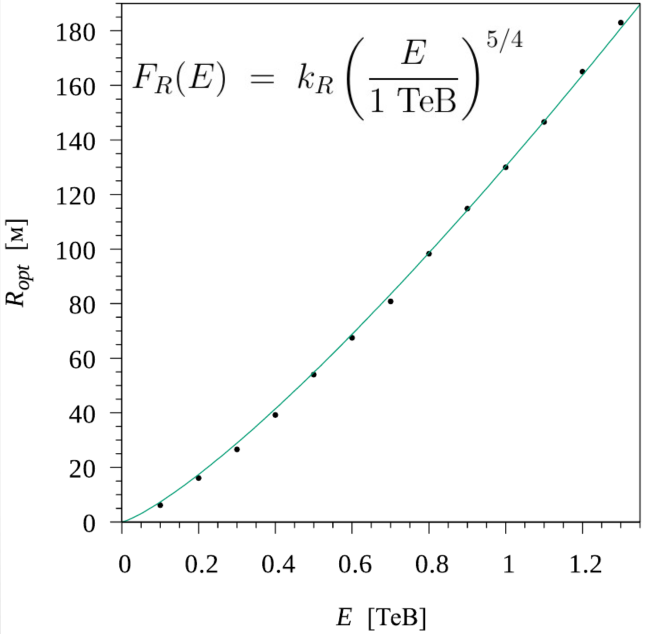
$$\overline{\psi_{inc}^2} = \zeta L/E^2 \;\Rightarrow\; \alpha_{st} = \frac{\psi_m^2}{l/R + \zeta R/E^2} \;\Rightarrow\; R_{opt} = E\sqrt{l/\zeta}$$

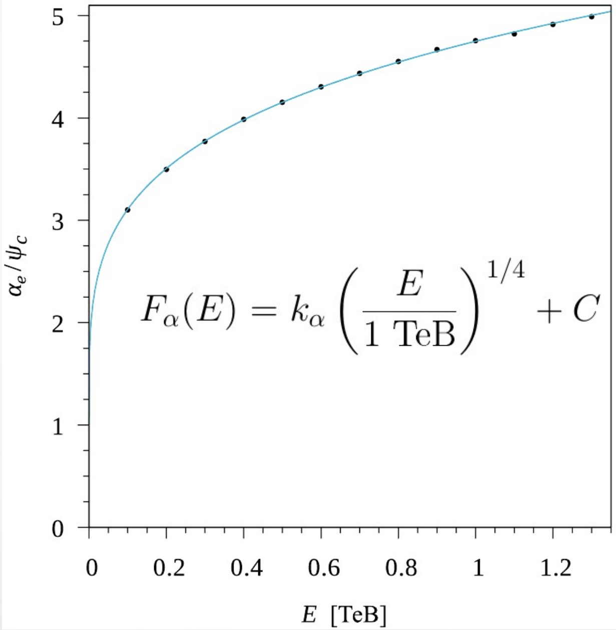
$$l \approx \frac{1}{4nda}\sqrt{\frac{E}{U_0}} \;\Rightarrow\; R_{opt} \propto E^{5/4}$$

$$\psi_m \approx 1,5\psi_c \propto E^{-1/2} \;\Rightarrow\; \max(\alpha_{st}) = \frac{\psi_m^2}{l/R_{opt} + \zeta R_{opt}/E^2} \propto E^{-1/4}$$

π^-, Si <110>







$k_R \approx 130$ м

$k_\alpha \approx 3,75$ і $C \approx 1$

Optimal radius of curvature (planar channeling)

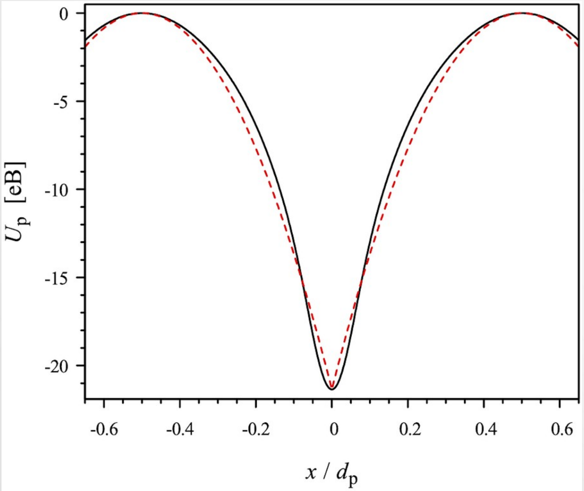
$$\frac{d^2x}{dt^2} = -\frac{c^2}{E}\frac{dU_{\text{eff}}(x)}{dx}$$

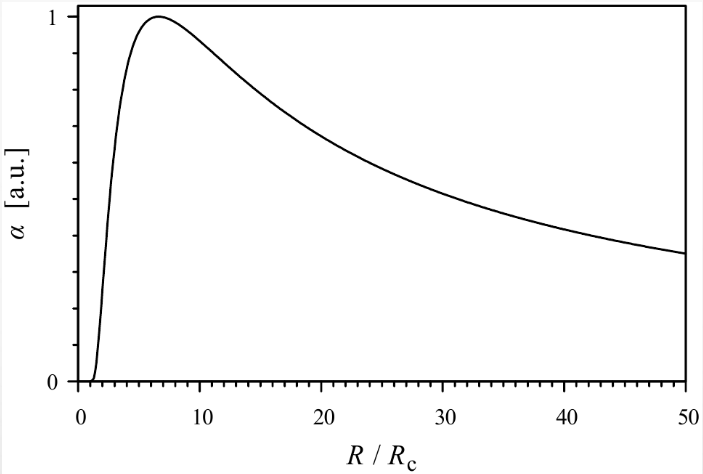
$$U_{\text{eff}}(x) = U_{\text{p}}(x) + Ex/R$$

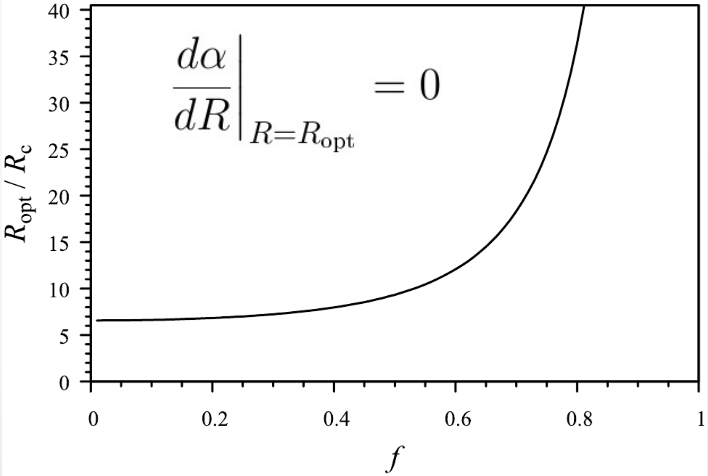
$$U_{\text{p}}(x) = -\frac{U_0}{d_{\text{p}}^2}\left((2x+d_{\text{p}})^2 H(-x(d_{\text{p}}+x)) + \right.$$
$$\left. + (2x-d_{\text{p}})^2 H(x(d_{\text{p}}-x))\right)$$

$R > R_{\text{c}}$ → $$\frac{x_{\text{pos}} - x_{\text{neg}}}{d_{\text{p}}} = 1 - \sqrt{\frac{R_{\text{c}}}{R}}$$

$$\alpha = \frac{l}{R} = \frac{\theta_{\text{c}}^2}{2\xi_{\text{p}}^2 R \left(\text{erf}^{-1}\left(\frac{f}{1-\sqrt{\frac{R_{\text{c}}}{R}}}\right)\right)^2}$$



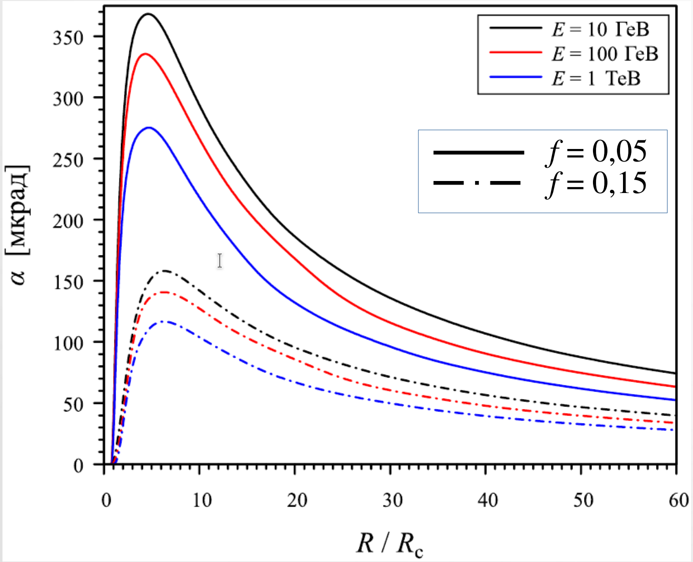


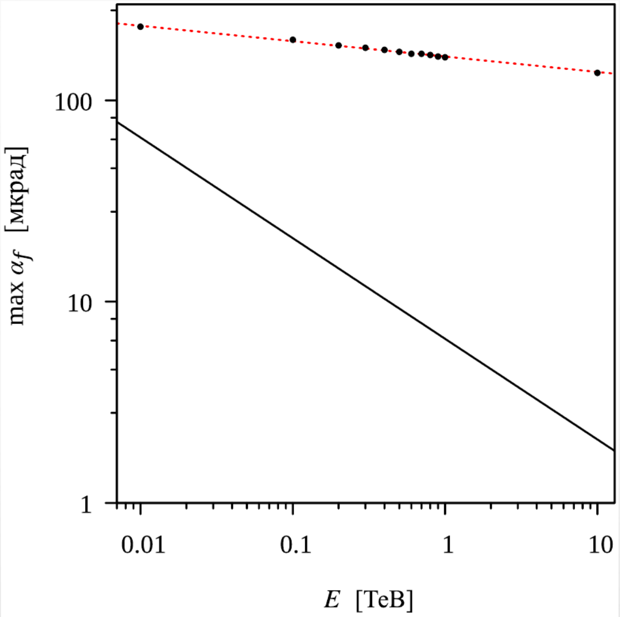


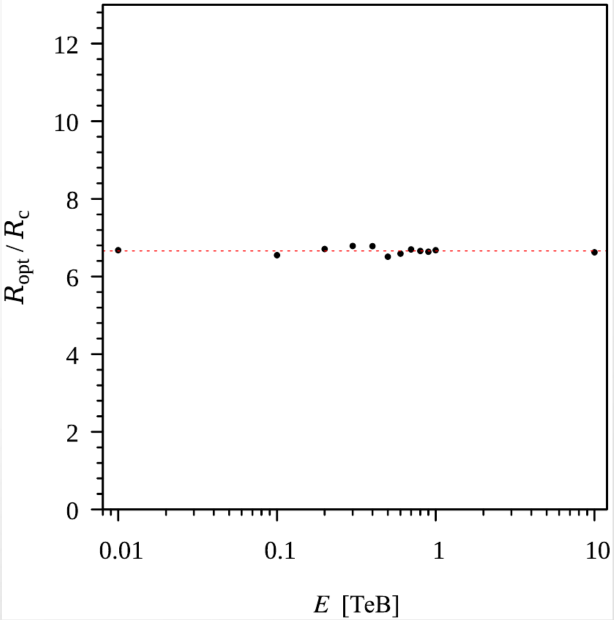
Optimal radius of curvature (planar channeling)

$$U_{\text{str}}(\rho) = -\frac{8\pi^2\hbar^2}{m_e d}\sum_{k=1}^{4}\frac{\alpha_k}{\beta_k+B}e^{-\frac{4\pi^2\rho^2}{\beta_k+B}} \rightarrow U_{\text{pl}}(x) = -\frac{4\pi^{\frac{3}{2}}\hbar^2}{m_e d d_s}\sum_{k=1}^{4}\frac{\alpha_k}{\sqrt{\beta_k+B}}e^{-\frac{4\pi^2x^2}{\beta_k+B}}$$

$$U_p(x) = \sum_{n=-\infty}^{\infty} U_{\text{pl}}(x-x_n) \rightarrow U_p(x) = -\frac{2\pi\hbar^2}{m_e d d_s d_p}\sum_{k=1}^{4}\alpha_k\theta_3\left(\pi\frac{x}{d_p}, e^{-\frac{\beta_k+B}{4d_p^2}}\right)$$







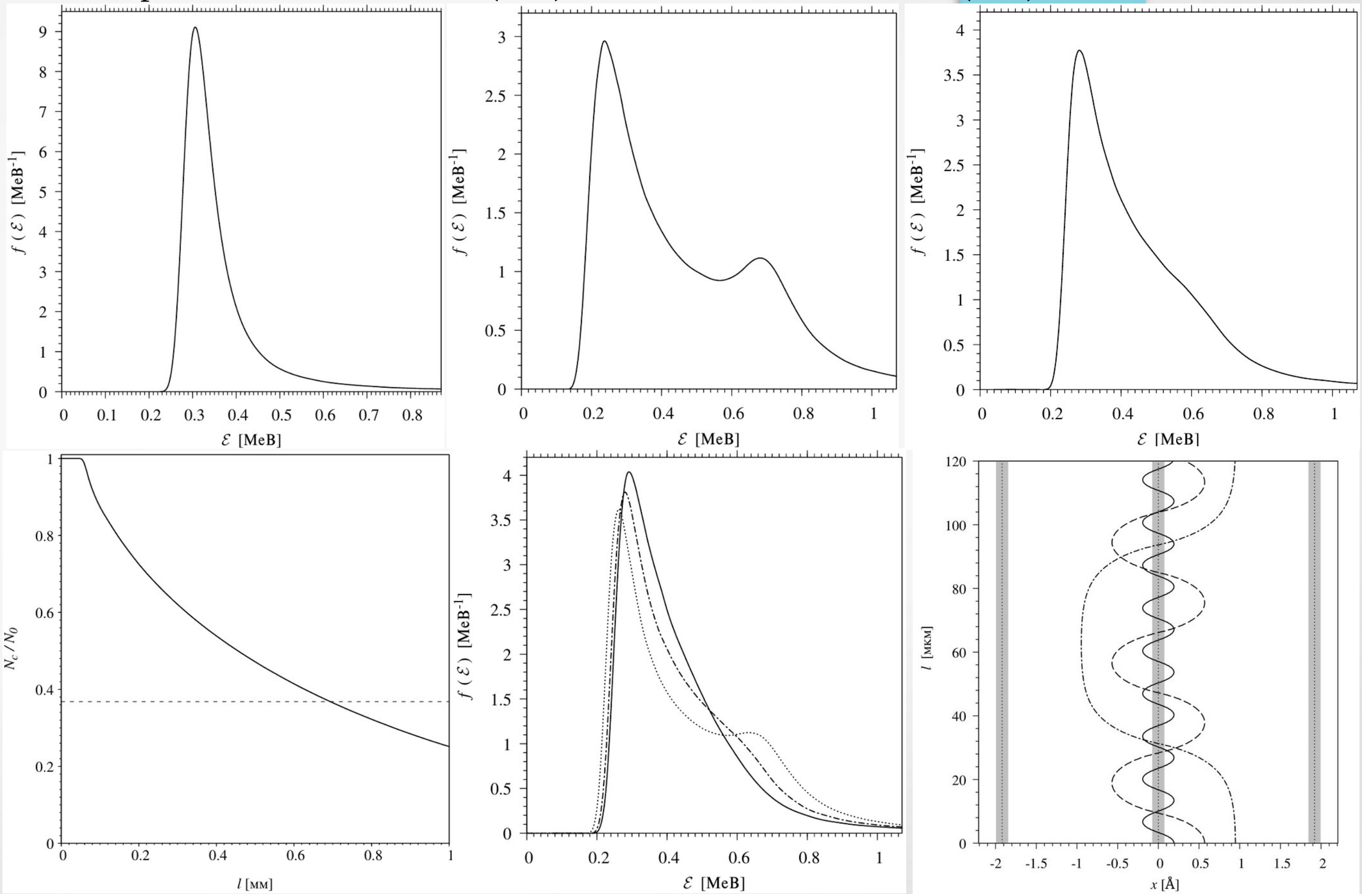
Ionization loss in a crystal

π^-, E=150 ГэВ, Si, L=1 мм

$$l_d = \xi E$$

Площина	Частинки	E [ГеВ]	ξ [мкм/ГеВ]	Джерело
(110)	e^-		17,8	[353]
(110)	e^-	0,855	21,1	[107]
(110)	e^-	0,855	48,0	[354]
(110)	e^-	0,855	9,7	[355]
(110)	e^-	1,2	24,2	[356]
(110)	π^-	150	6,2	[357]
(111)	e^-		23,6	[353]
(111)	e^-	0,855	23,7	[358]
(111)	e^-	0,855	15,9	[355]
(111)	e^-	3,35–14	15,3	[187]
(111)	e^-	0,5–100	27	[359]
(111)	e^-	50	6,6	[360]

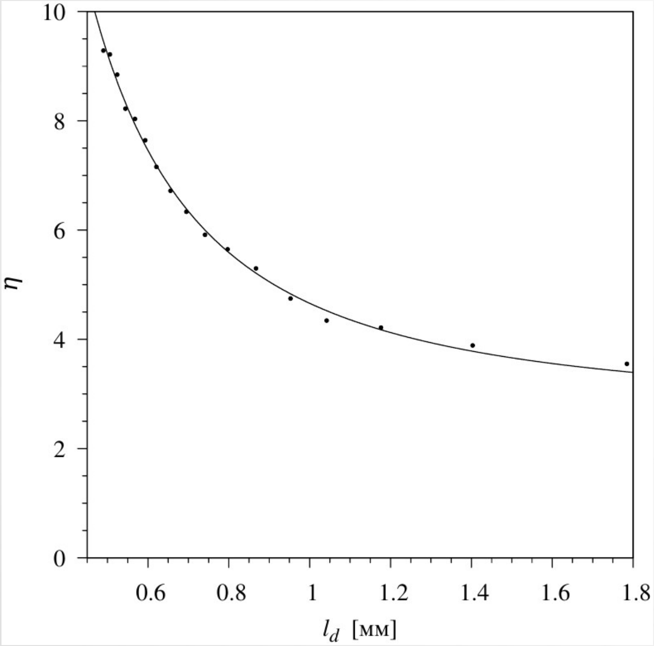
amorphous orientation | (110) without incoh. scatt. | (110) with incoh. scatt.

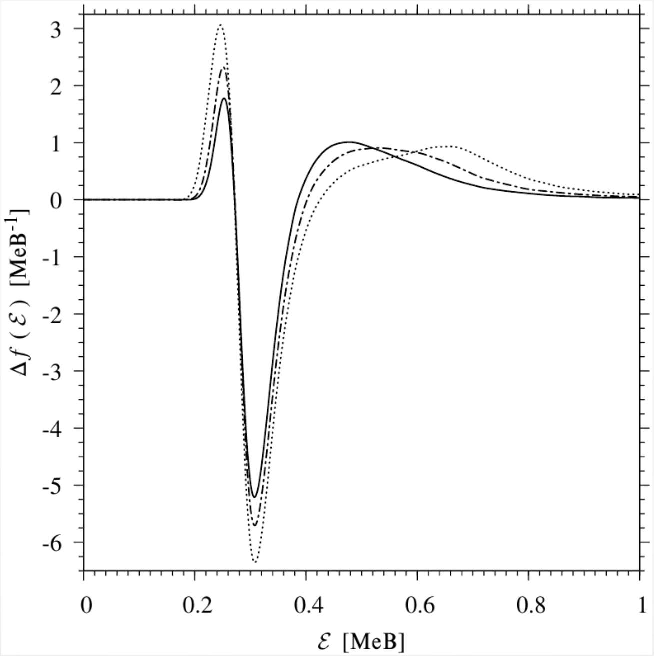


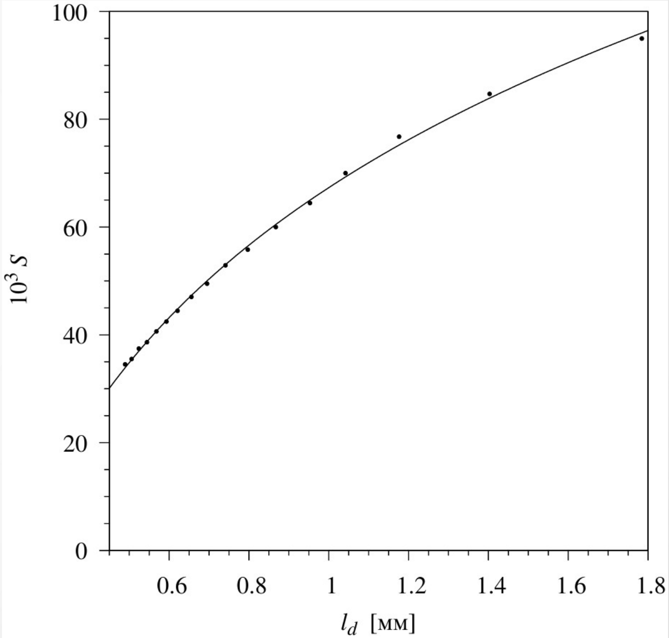
Ionization loss in a crystal

$$\eta = f(\mathcal{E}_{\max})/f(\mathcal{E}_R)$$

$\mathcal{E} < \mathcal{E}_L$ $\mathcal{E}_L \approx 250$ keV







Trofymenko S.V., Kyryllin I.V. Eur. Phys. J. C. 2020. Vol. 80. P. 689 (1–6).

Дякую за увагу!