RECENT INVESTIGATIONS ON DISTRIBUTIONS OF HIGH-ENERGY PARTICLE IONIZATION ENERGY LOSS IN STRAIGHT AND BENT CRYSTALS

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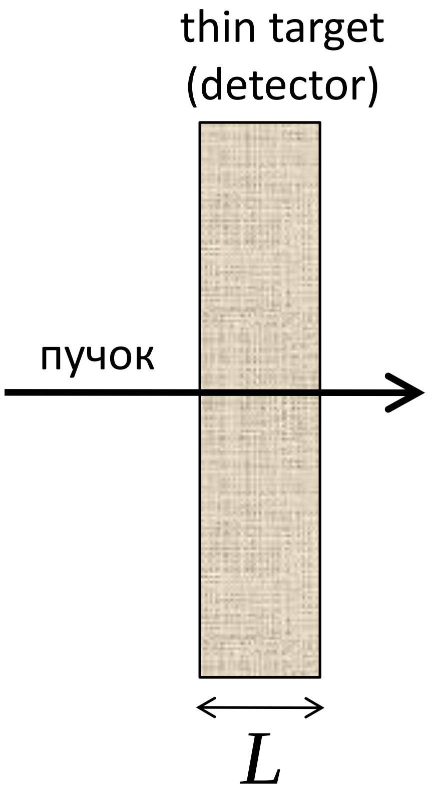
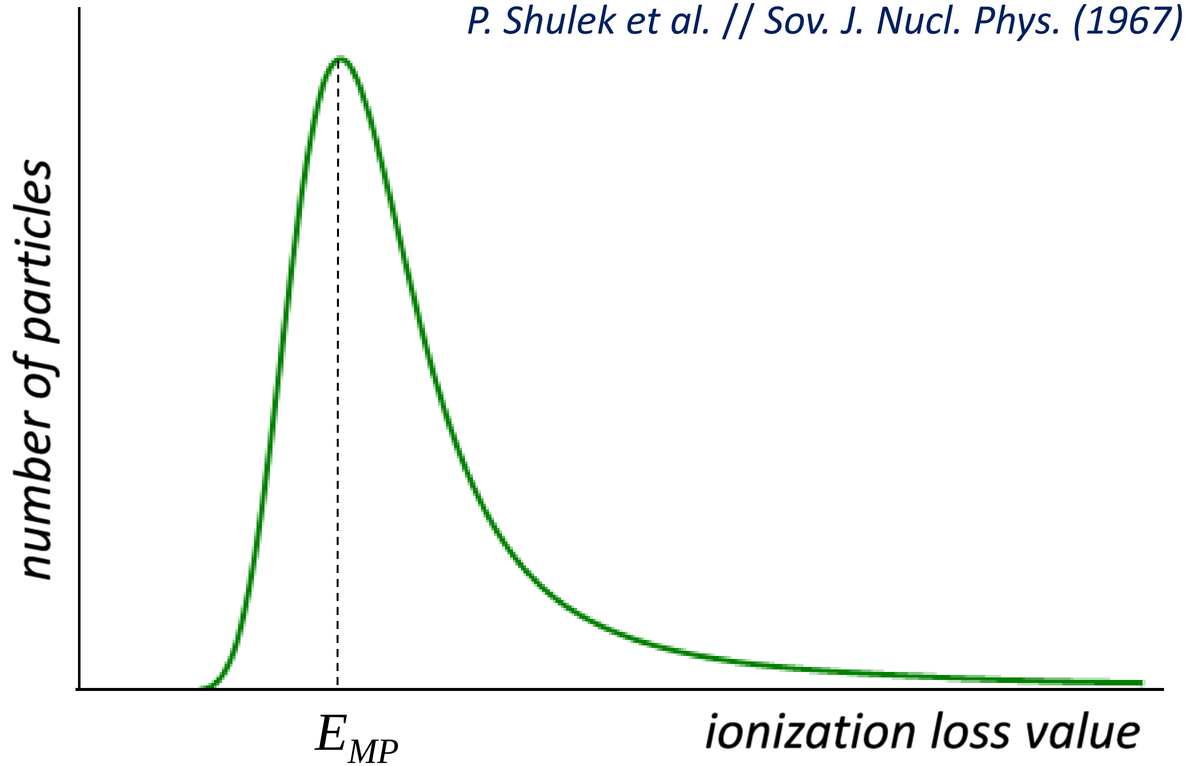
In memory of N.F. Shul'ga

LANDAU DISTRIBUTION (SPECTRUM) IN AMORPHOUS TARGET

L.D. Landau // J. Phys. USSR (1944)
P.V. Vavilov // Sov. Phys. JETP (1957)
P. Shulek et al. // Sov. J. Nucl. Phys. (1967)

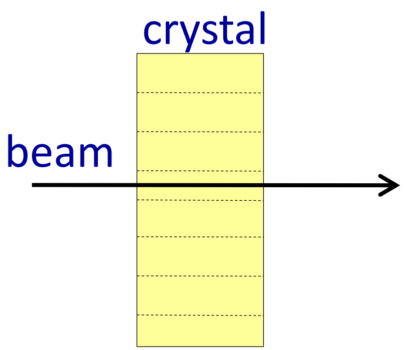




$$E_{MP} < \frac{dE}{dz} L = E_{AV}$$

$$E_{MP} \sim L \ln L$$

IONIZATION LOSS SPECTRUM IN AN ORIENTED CRYSTAL



from *H. Esbensen et al., Phys. Rev. B, 1978*

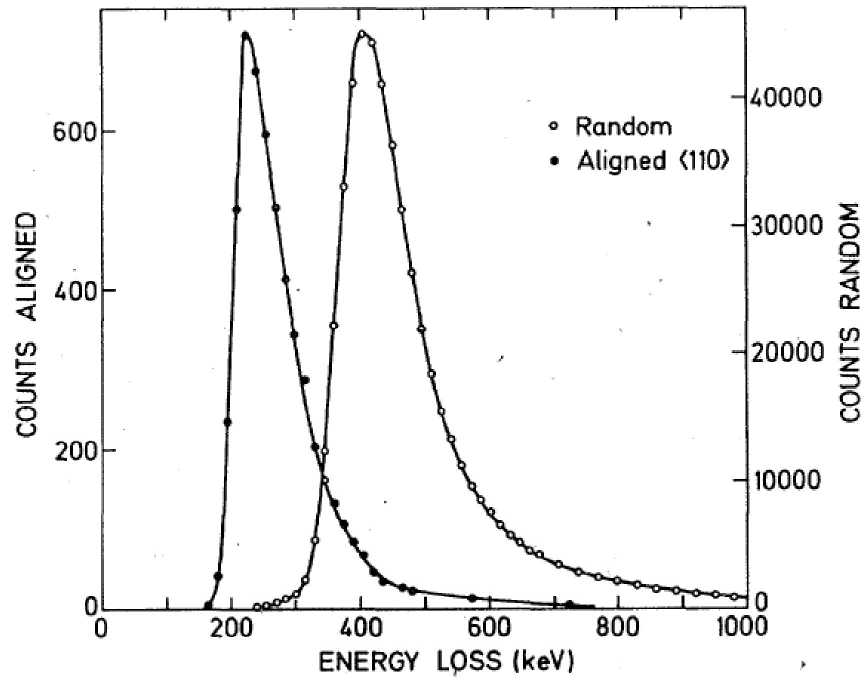


FIG. 6. Energy-loss spectra for 15-GeV/c protons incident on a 0.74-mm Ge single crystal. The dots correspond to particles channeled along a ⟨110⟩ axis, and the circles correspond to particles incident in a "random" direction.

Open questions:

- orientational effects
- ion. loss spectra in bent crystals
- negative particles
- …

METHOD OF SIMULATION OF THE IONIZATION LOSS IN ORIENTED CRYSTALS

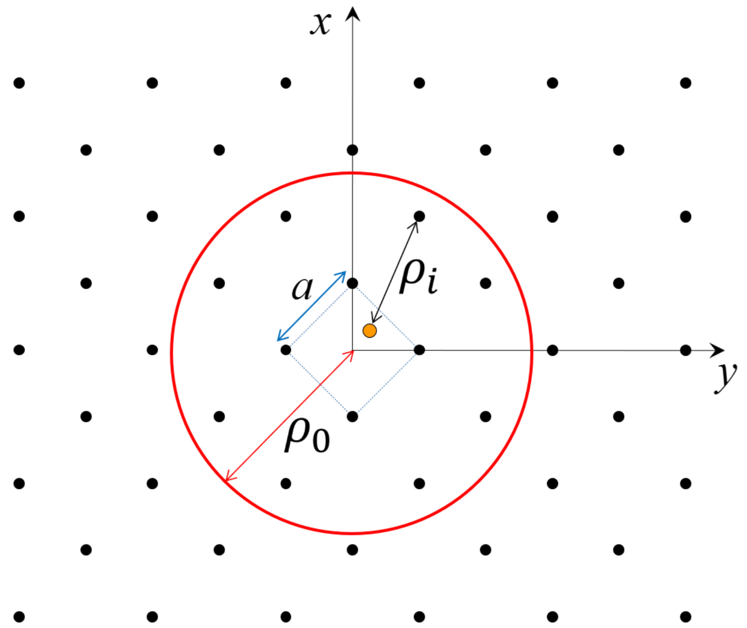
Probability of an atomic electron excitation:

$$w_{jb_k}(\rho) = \frac{4e^4}{\hbar^2 v^4} \left| x_{jb_k} \right|^2 \left\{ \frac{\omega_{jb_k}^2}{v^2\gamma^4} K_0^2(\Omega_{jb_k}\rho) + \Omega_{jb_k}^2 K_1^2(\Omega_{jb_k}\rho) \right\}$$

where:

$$\Omega_{jb_k}^2 = \frac{\omega_{jb_k}^2}{v^2\gamma^4} + \frac{\omega_p^2}{c^2}$$

$$x_{jb_k} = \langle j|x|b_k\rangle$$



effective cross-section:

$$\frac{d\sigma_d(x,y)}{d\varepsilon} = \frac{2\pi e^4}{mc^2} \sum_k \frac{f_k}{\varepsilon_k} \left\{ \ln \frac{v^2\gamma^2\hbar^2}{(\varepsilon_k^2 + \hbar^2 l^2)\rho_0^2} + \frac{l^2}{\omega_p^2\gamma^2} - \right.$$

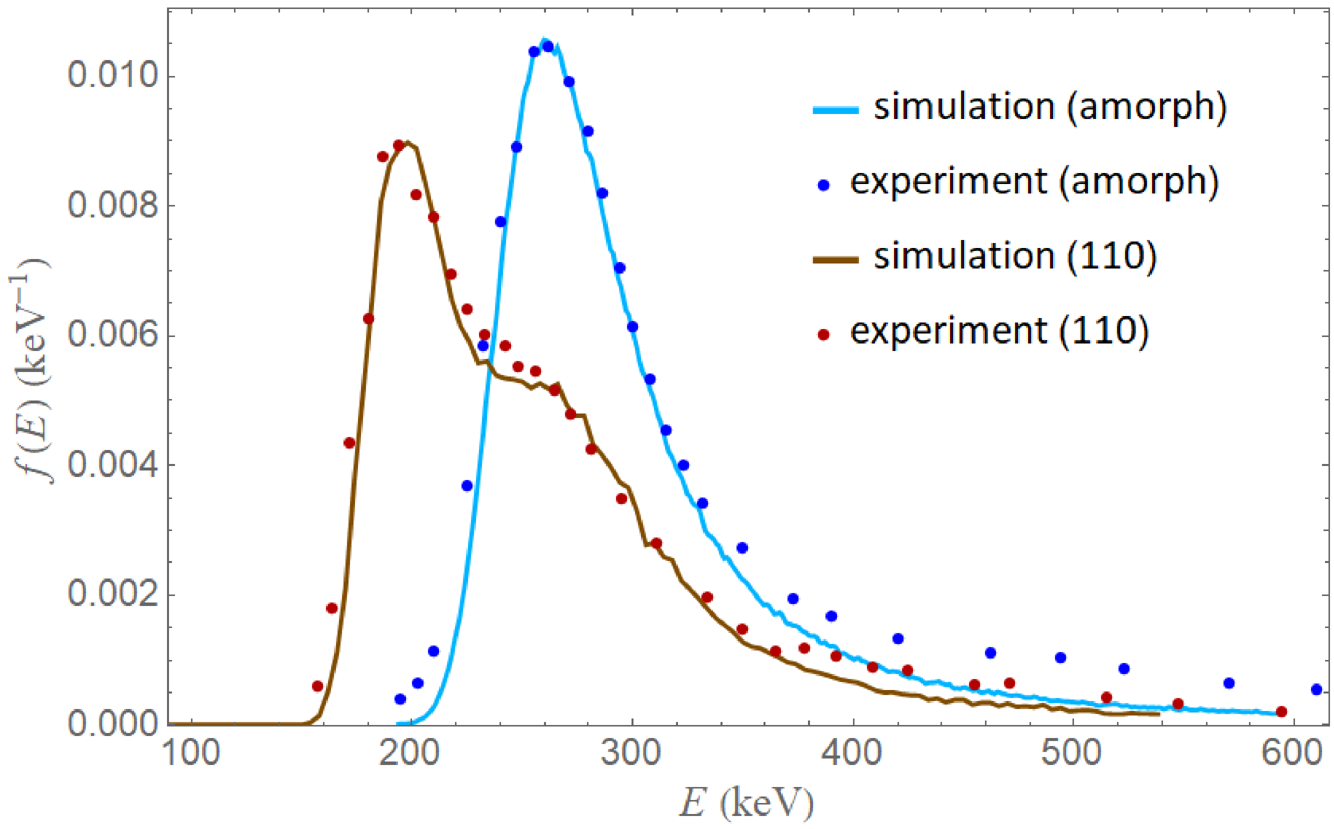
$$\left. - \frac{v^2}{c^2} + F_k(x,y) \ln \frac{2m\varepsilon_k\rho_0^2}{\hbar^2} \right\}$$

where:

$$F_k(x,y) = \frac{1}{\pi\varkappa} \sum_i \frac{1 - \exp\{[(x-x_i)^2 + (y-y_i)^2]/b_k^2\}}{(x-x_i)^2 + (y-y_i)^2} \left(\ln \frac{2m\varepsilon_k\rho_0^2}{\hbar^2} \right)^{-1}$$

COMPARISON OF SIMULATION WITH EXPERIMENT

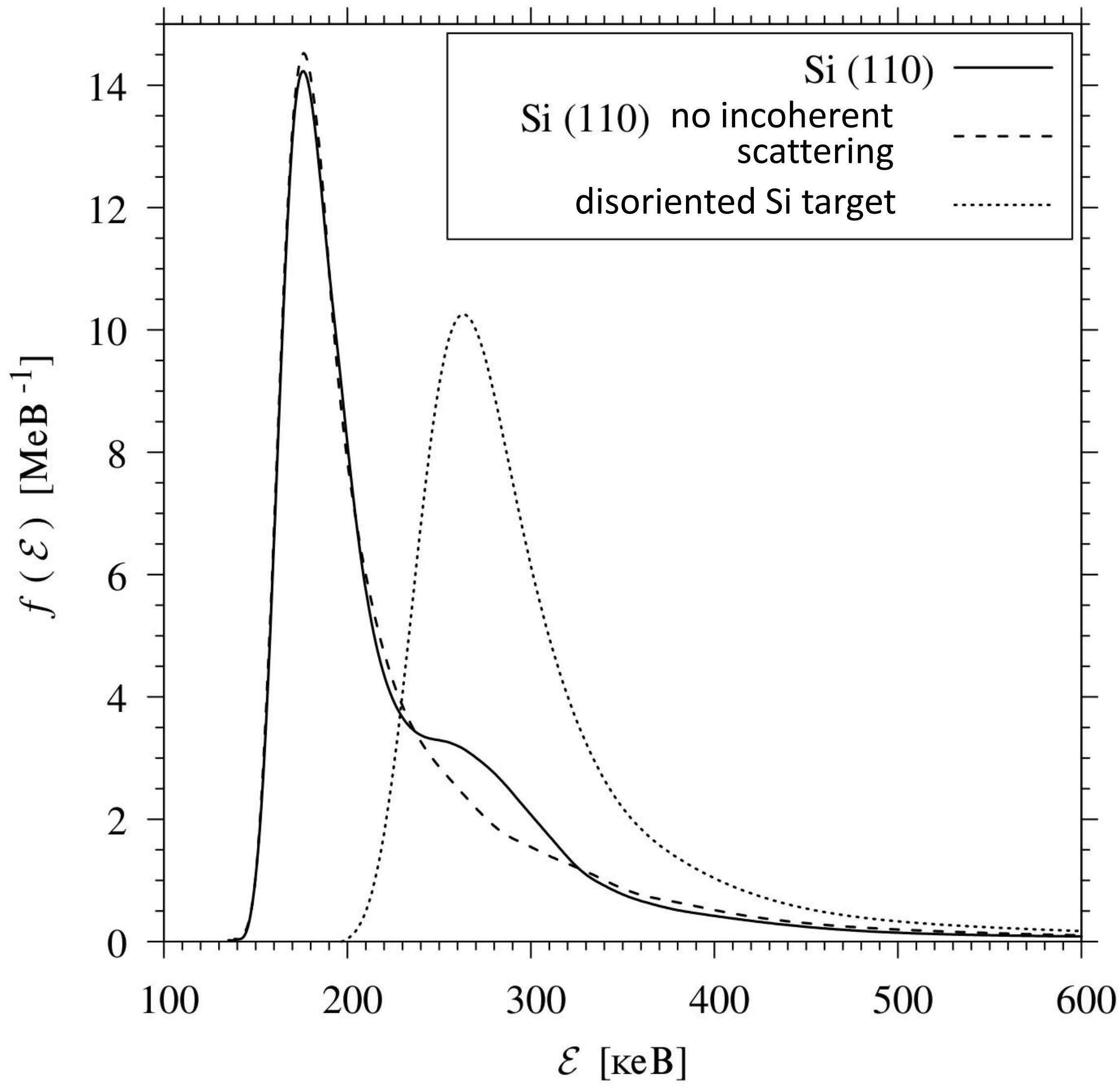
Ionization loss spectra of 15 GeV/c protons at 'amorphous' and planar (110) orientation in 900 μm Si crystal:



Experiment: H. Esbensen et al., Phys. Rev. B 18, 1039 (1978)

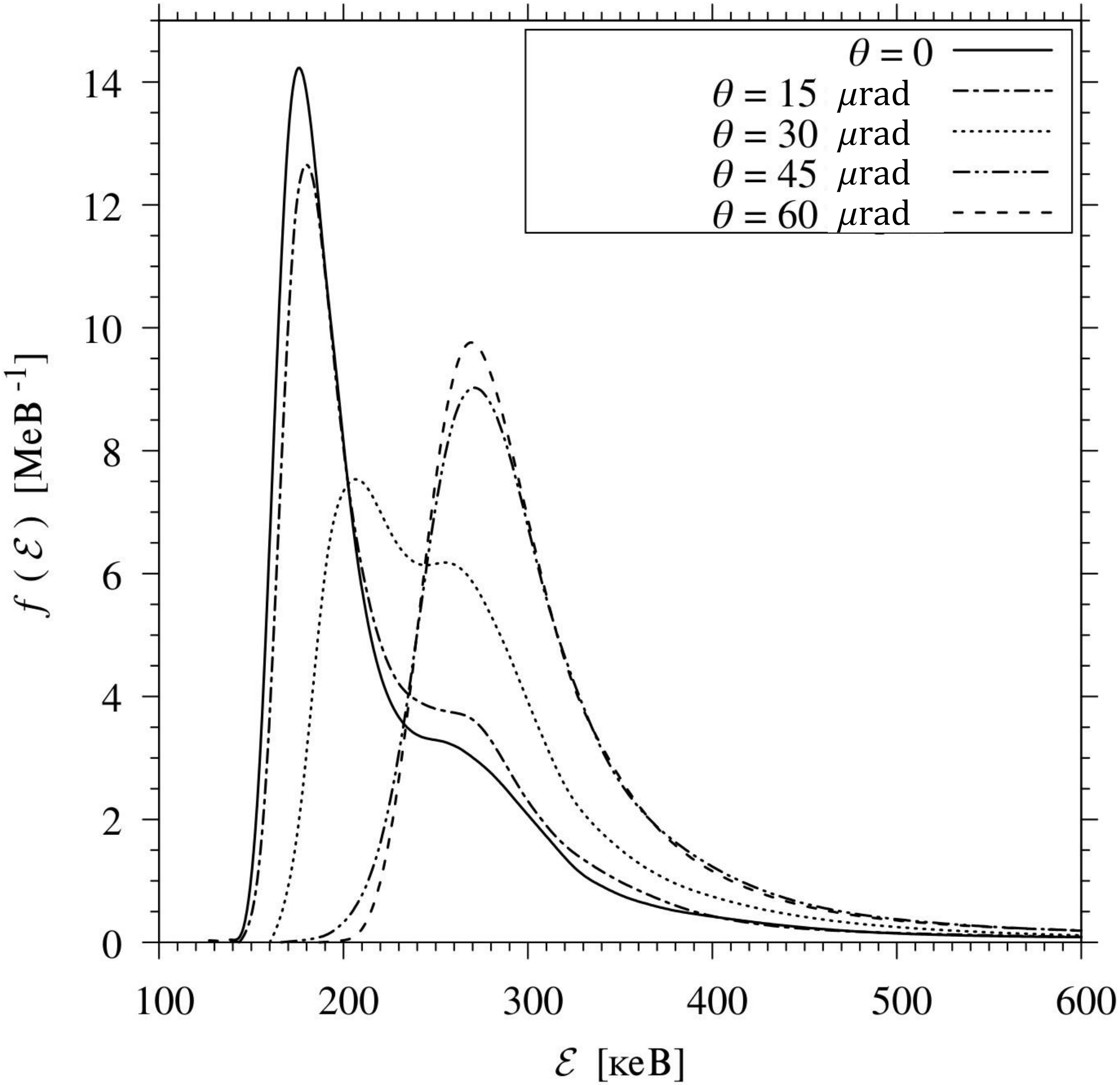
PLANAR ORIENTATION (110)

Ionization loss spectra of 15 GeV/c protons at 'amorphous' and planar (110) orientation in 900 μm Si crystal (no beam divergence):

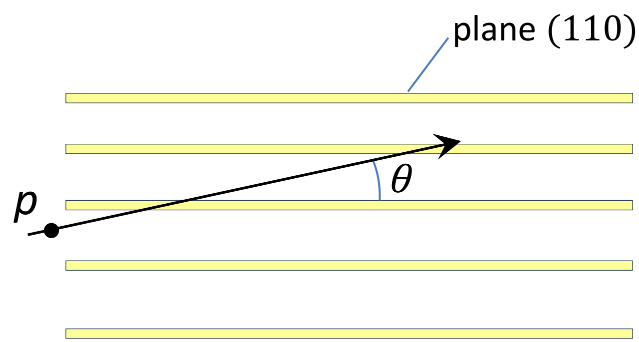


TRANSITION: PLANE (110) ⟶ «AMORPHOUS» ORIENTATION

Ionization loss spectra of protons at different angles θ between the particle momentum and plane:

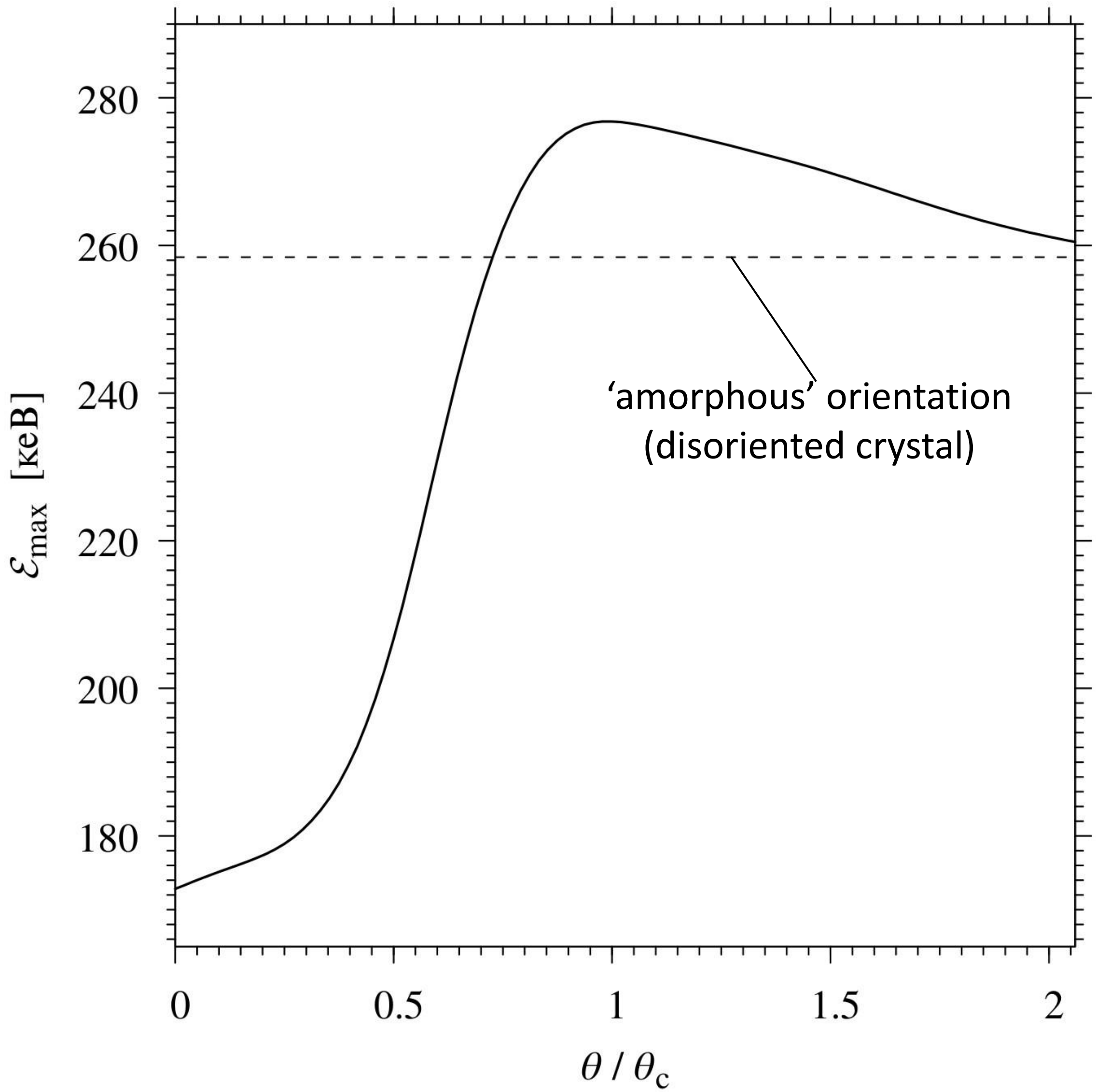


$$\theta_c = 53.4\ \mu rad$$



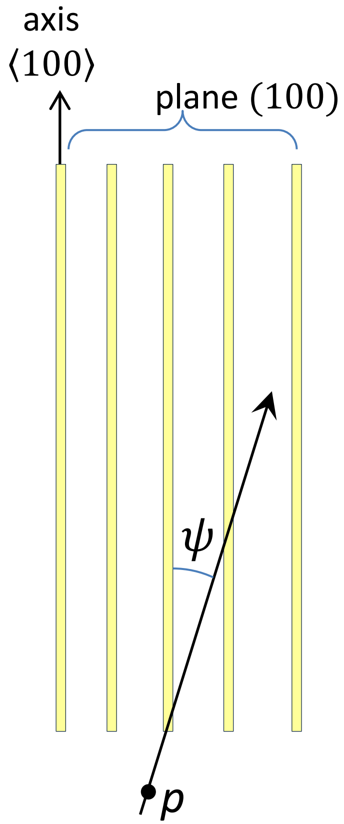
TRANSITION: PLANE (110) ⟶ «AMORPHOUS» ORIENTATION

Most probable value of ionization loss as a function of the angle θ between the particle momentum and plane:



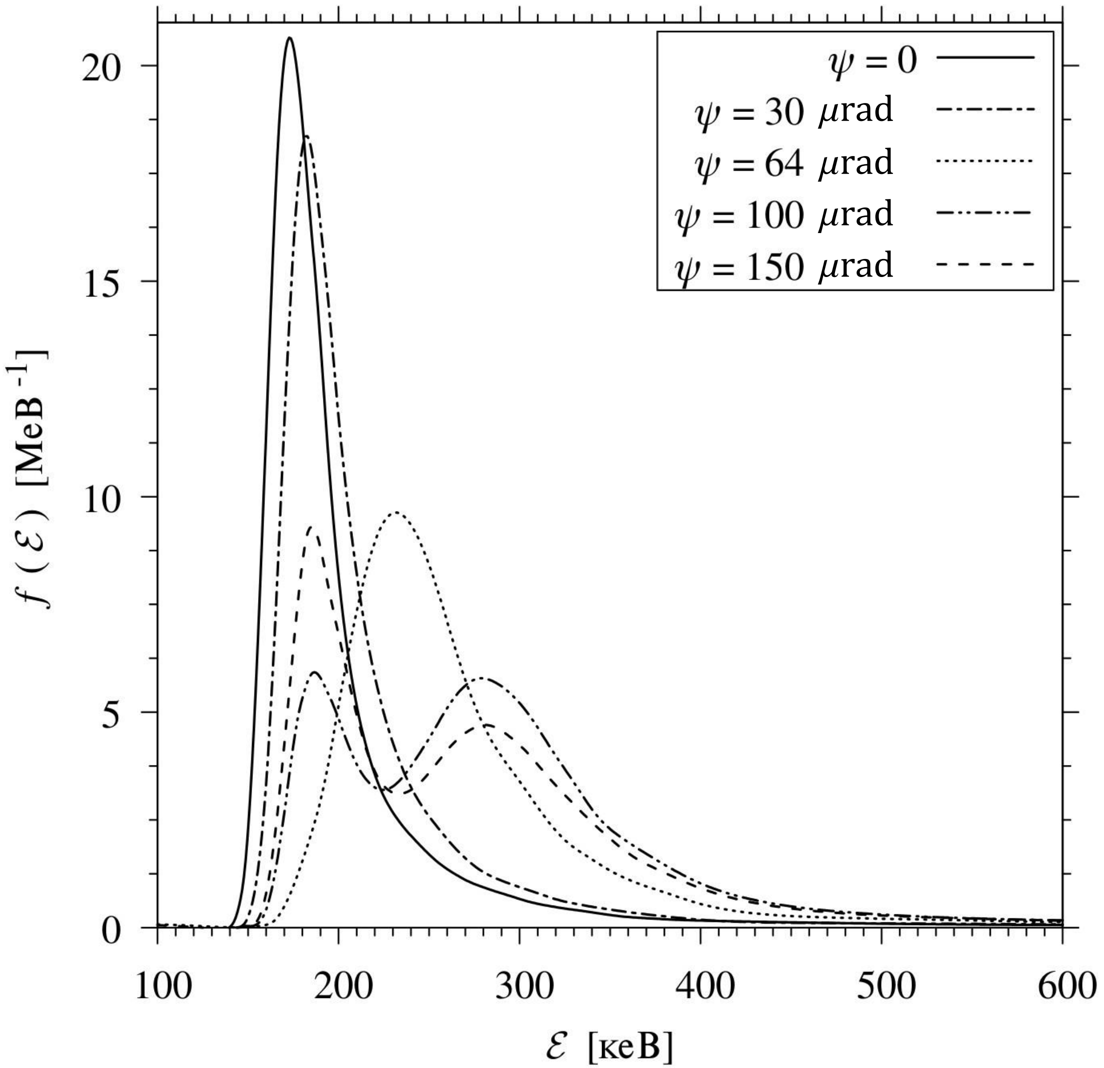
$\theta_c = 53.4\,\mu rad$

TRANSITION: AXIS ⟨100⟩ ⟶ PLANE (100)



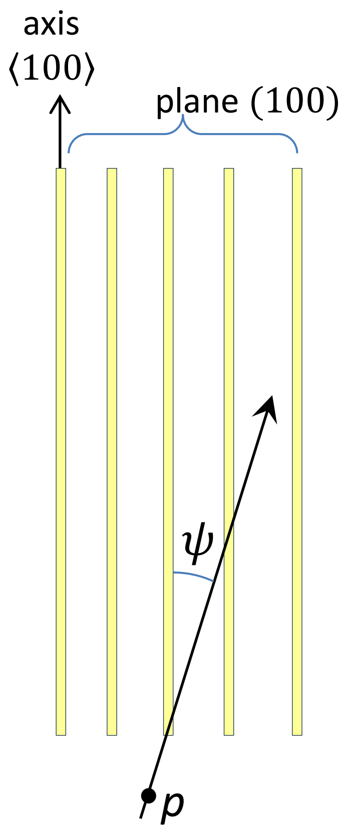
$\psi_c = 99.6\ \mu rad$

Ionization loss spectra of protons at different angles
ψ between the particle momentum and axis:

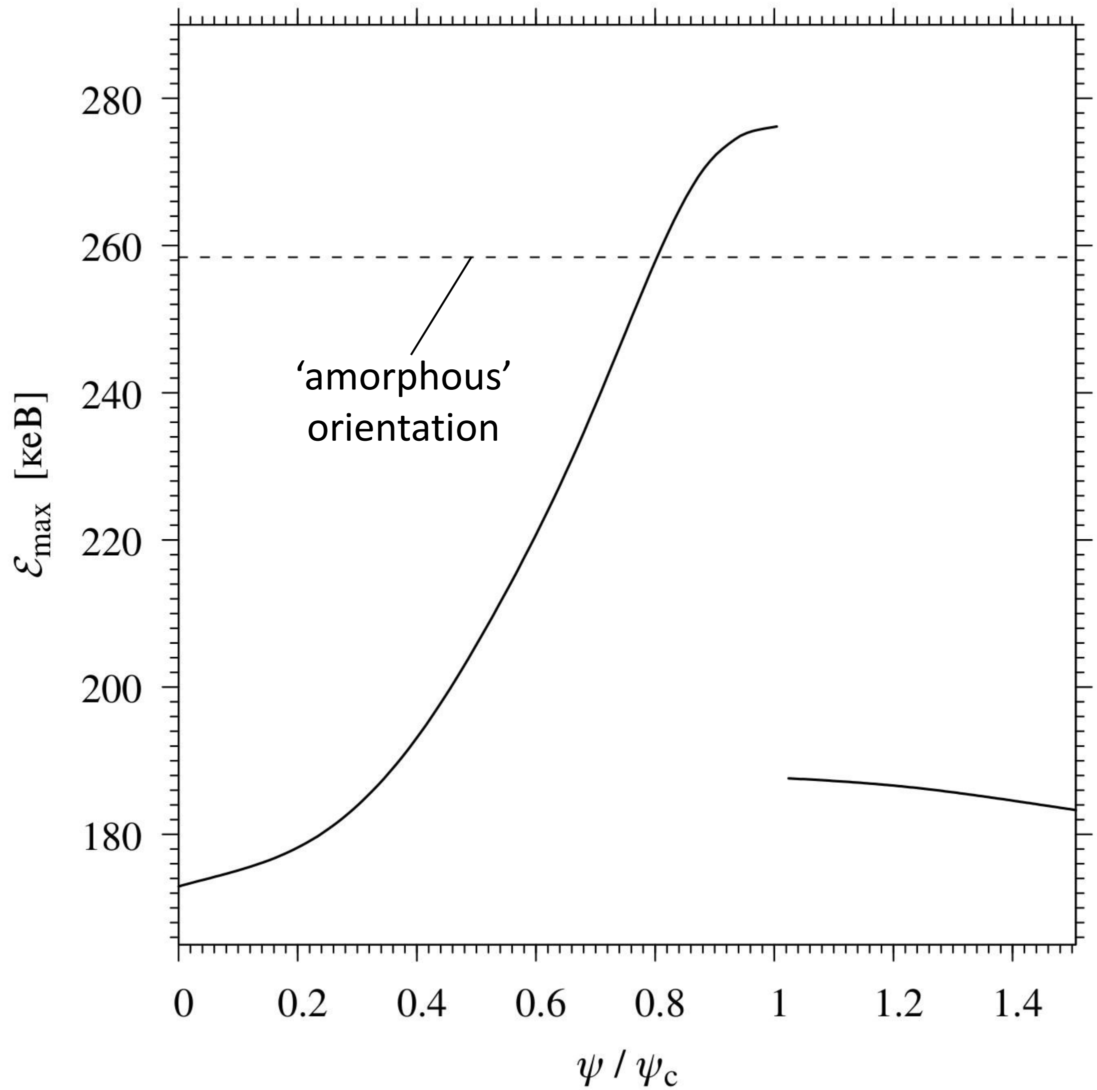


TRANSITION: AXIS ⟨100⟩ ⟶ PLANE (100)

Most probable value of ionization loss as a function of the angle ψ between the particle momentum and axis :

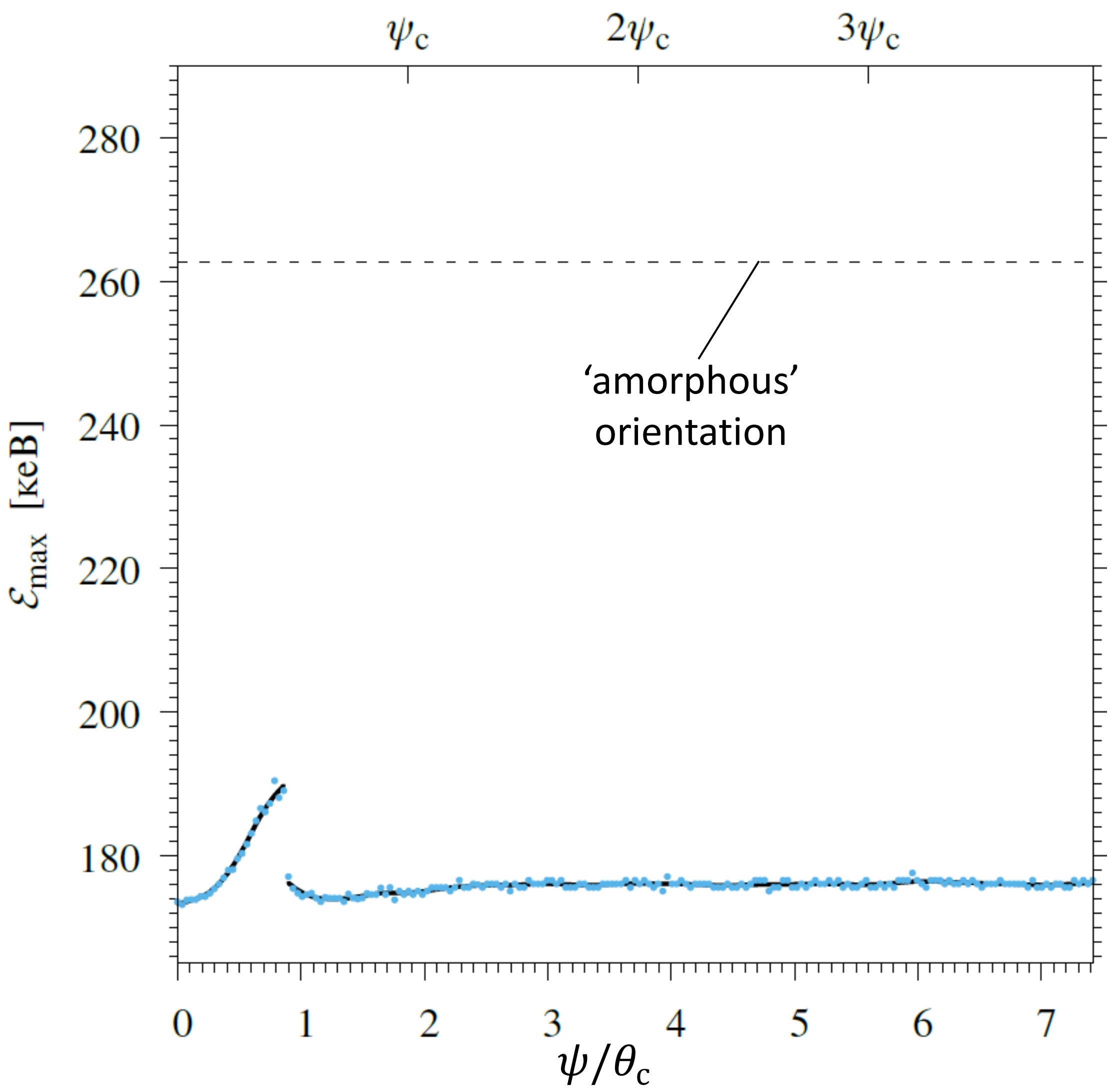


$$\psi_c = 99.6\,\mu rad$$



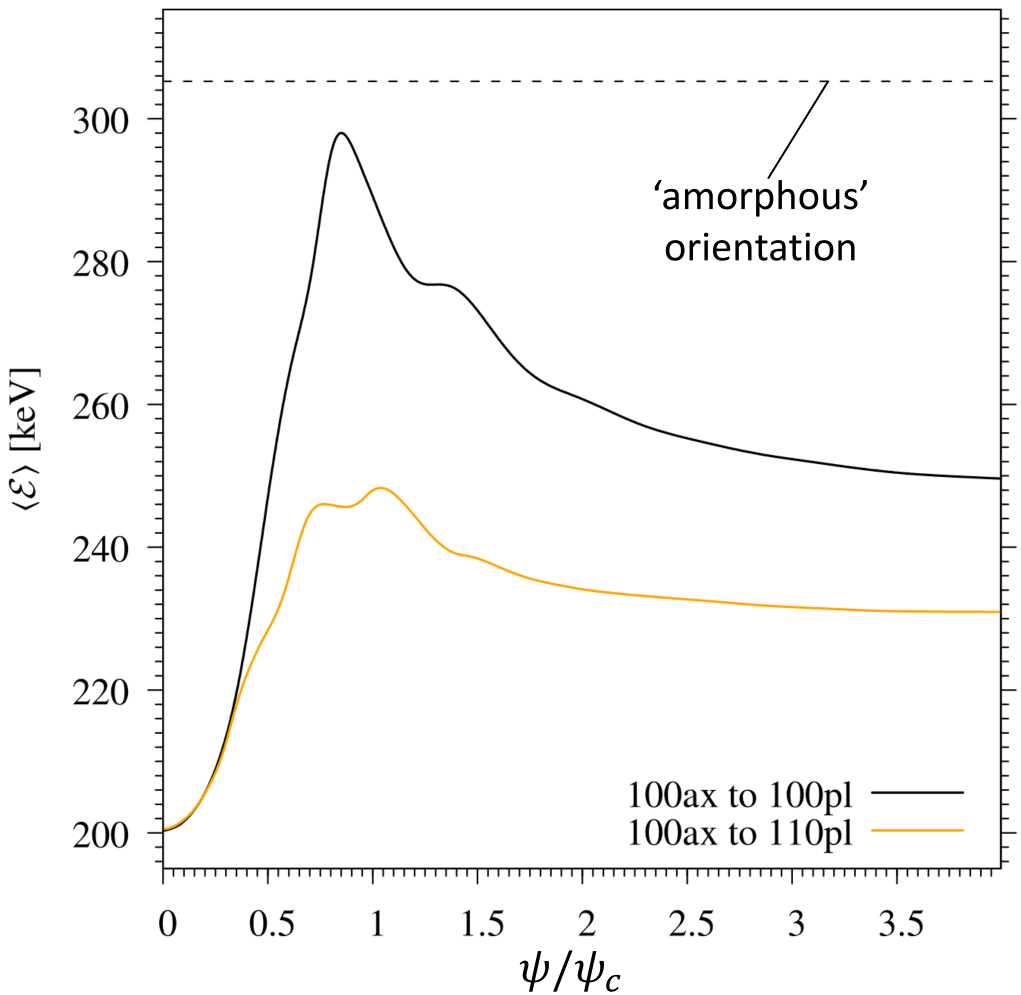
TRANSITION: AXIS ⟨100⟩ ⟶ PLANE (110)

Most probable value of ionization loss as a function of the angle ψ between the particle momentum and axis :



TRANSITION: AXIS ⟨100⟩ ⟶ PLANES (110) AND (100)

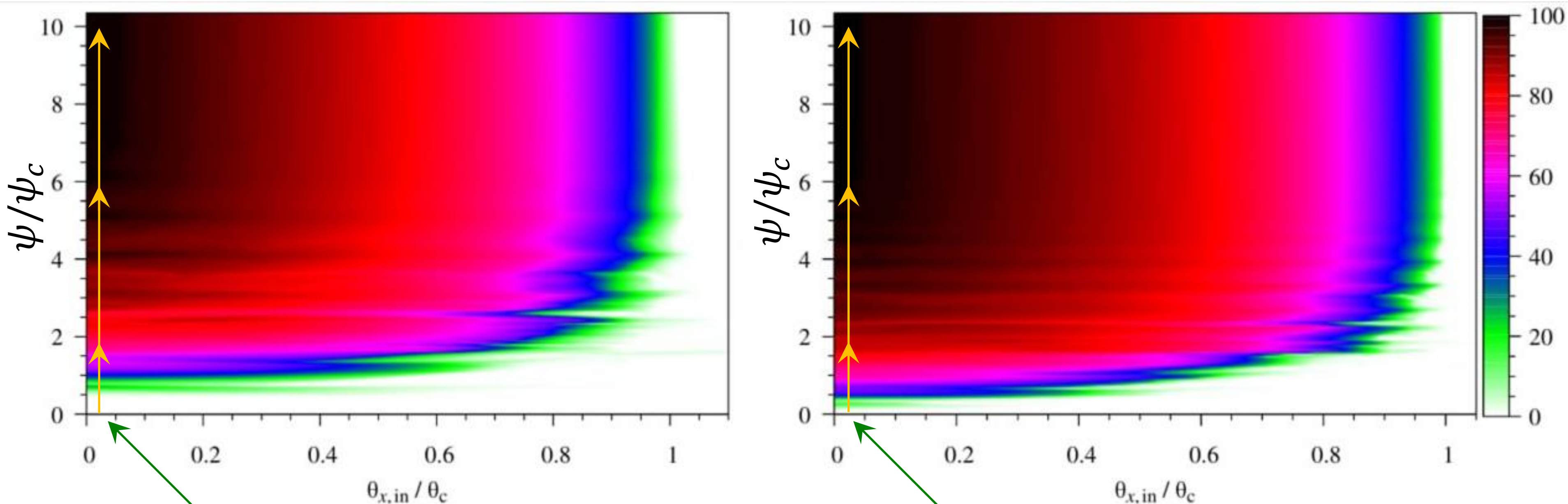
Mean ionization loss value as a function of the angle ψ between the particle momentum and axis:



TRANSITION: AXIS ⟨100⟩ ⟶ PLANES (100) AND (110)

Kyryllin I.V., Shul’ga N.F. *J. Instrum.* 13 (2018) C02020

Dependence of the number of particles which move in the planar channeling mode on the angle ψ between the particle momentum and axis ⟨100⟩ :

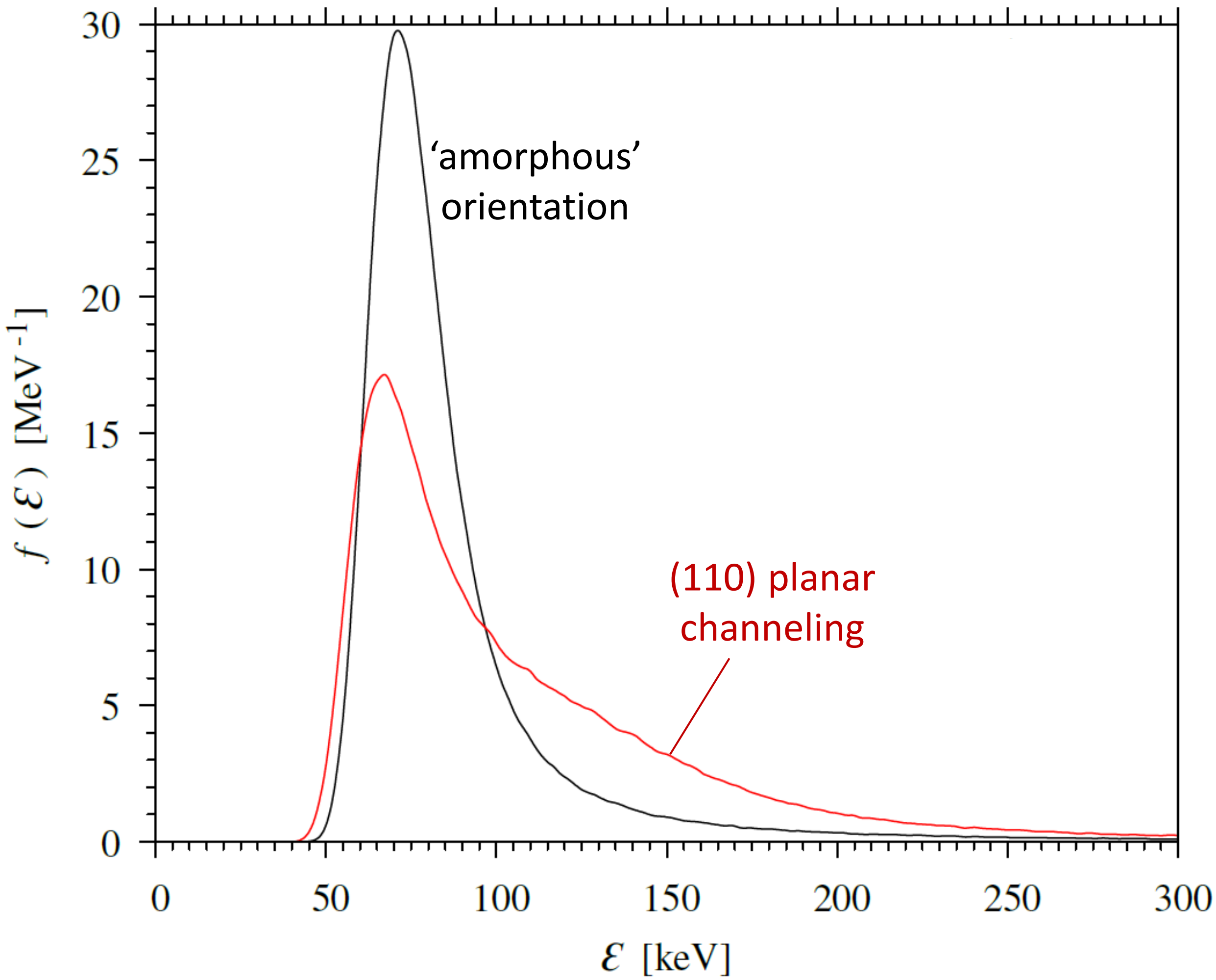


transition from axis ⟨100⟩ to plane (100)

transition from axis ⟨100⟩ to plane (110)

NEGATIVE PARTICLES

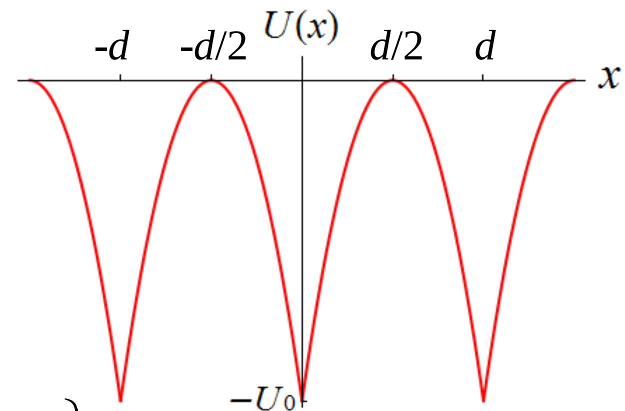
Ionization loss spectra for 150 GeV π^- mesons at planar channeling in (110) planes of 250 μm Si crystal and in amorphous target



ANALYSIS OF NEGATIVE CHANNELED PARTICLE MOTION

$$U(x) = -U_0\left[\left(2\frac{x}{d}-1\right)^2 H(x) + \left(2\frac{x}{d}+1\right)^2 H(-x)\right]$$

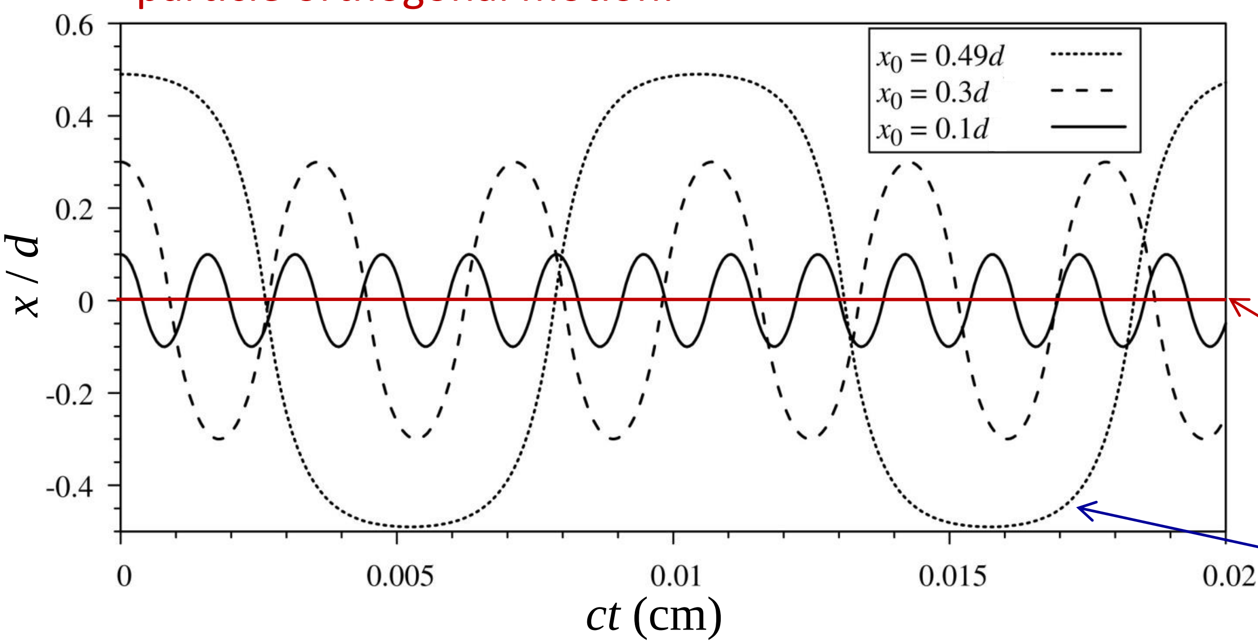
(110) planar potential:



$$\frac{d^2x}{dt^2} = -\frac{v}{p}\frac{\partial U(x)}{\partial x}$$

$$x(t) = d/2 + (x_0 - d/2)\,\mathrm{ch}\left\{\frac{2c}{d}\sqrt{\frac{2U_0}{pv}}\left[t - 2t_1\,\mathrm{R}\left(t/2t_1\right)\right]\right\}\mathrm{sgn}\left[\cos\left(\pi t/2t_1\right)\right]$$

particle orthogonal motion:



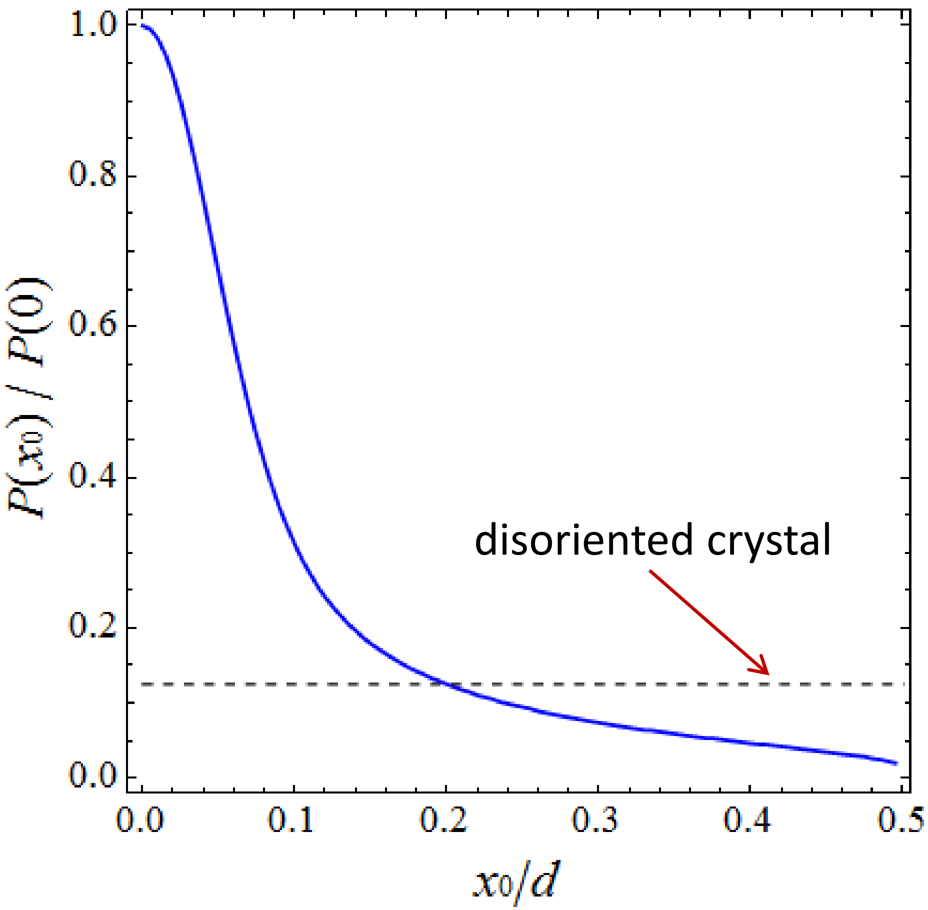
$$t_1 = \frac{1}{A}\,\mathrm{arch}\left(\frac{1}{1-2x_0/d}\right)$$

x_0 – impact parameter

crystalline plane

‘hanging’ mode of motion

PROBABILITY OF CLOSE COLLISIONS FOR CHANNELED NEGATIVE PARTICLES



Dependence of probability of close collisions of 150 GeV/c π^- mesons with atoms on the impact parameter (solid line)

$$\frac{P(x_0)}{P(0)} = L^{-1}\int_0^T \exp\left(-\frac{x^2(t)}{2r_T^2}\right)v(t)dt$$

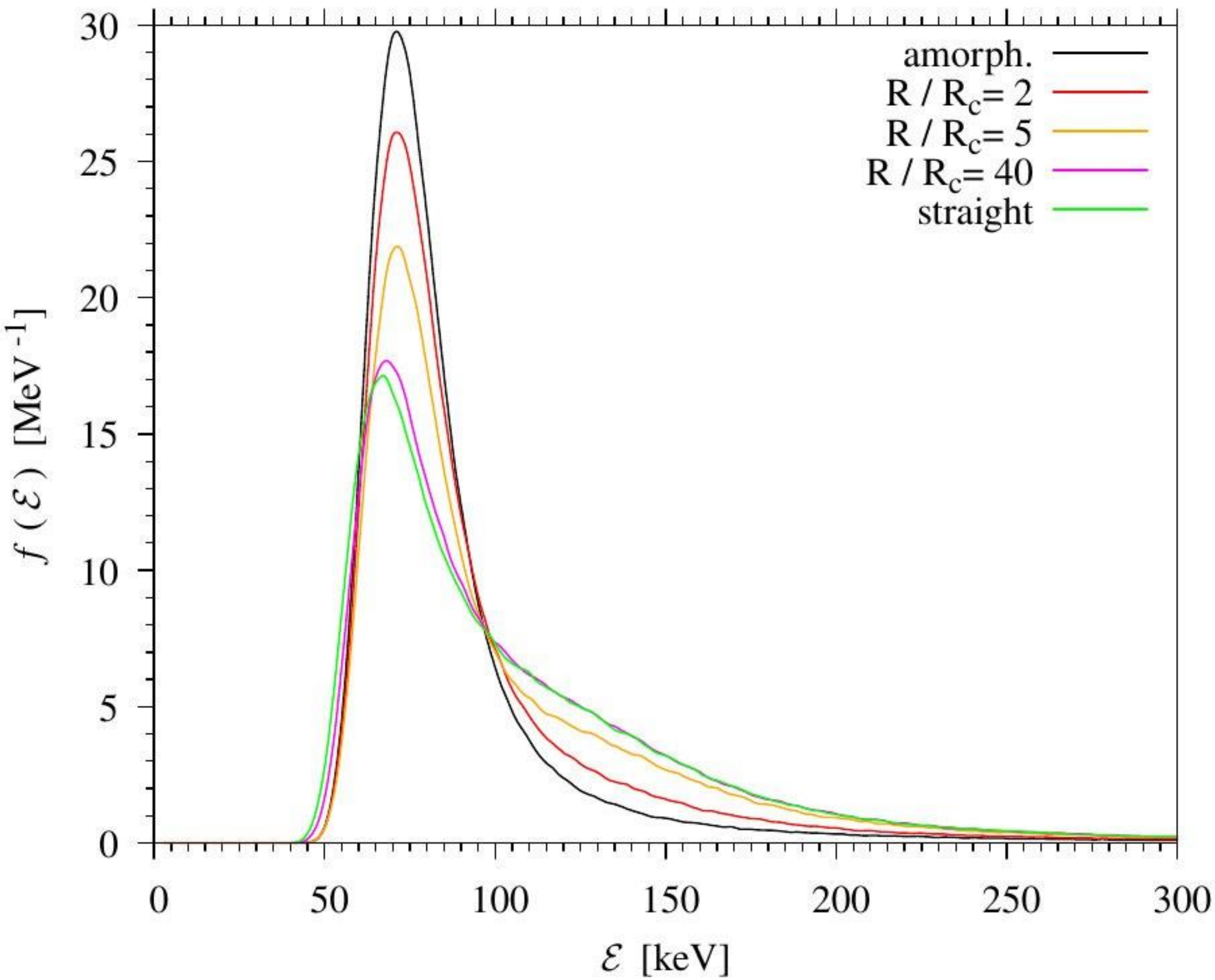
d – distance between planes

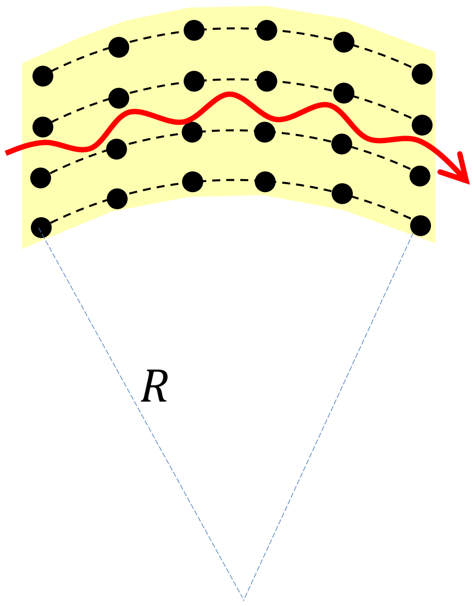
x_0 – impact parameter

For a disoriented crystal: $\bar{P}_{\text{dis}} = \frac{2}{\sqrt{\pi}\xi}\text{erf}(\xi)$, where $\xi = d/\left(2\sqrt{2}r_T\right)$

NEGATIVE PARTICLES IN A BENT CRYSTAL

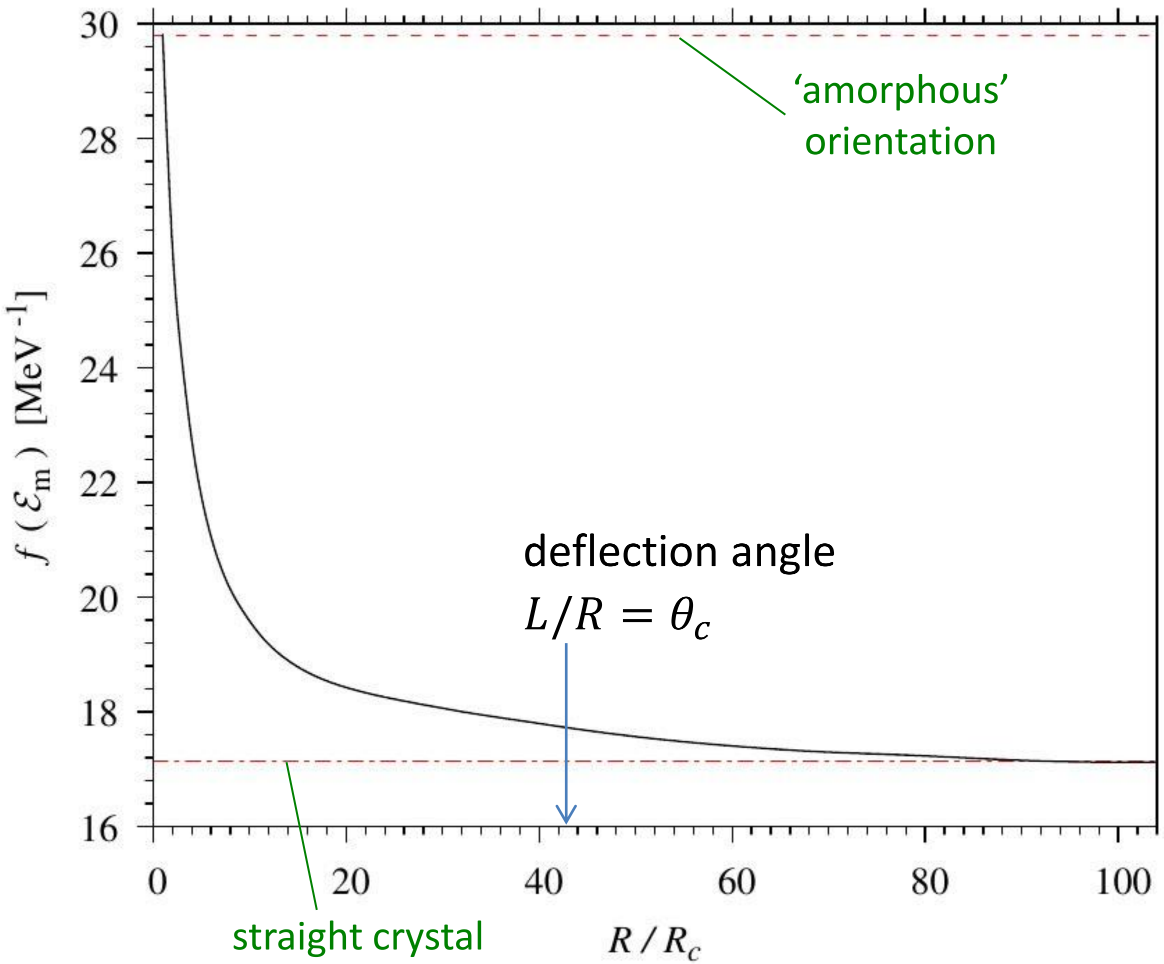
Ionization loss spectra for 150 GeV π^- mesons at planar channeling in (110) planes of 250 μm Si bent crystal for different values of the crystal curvature radius





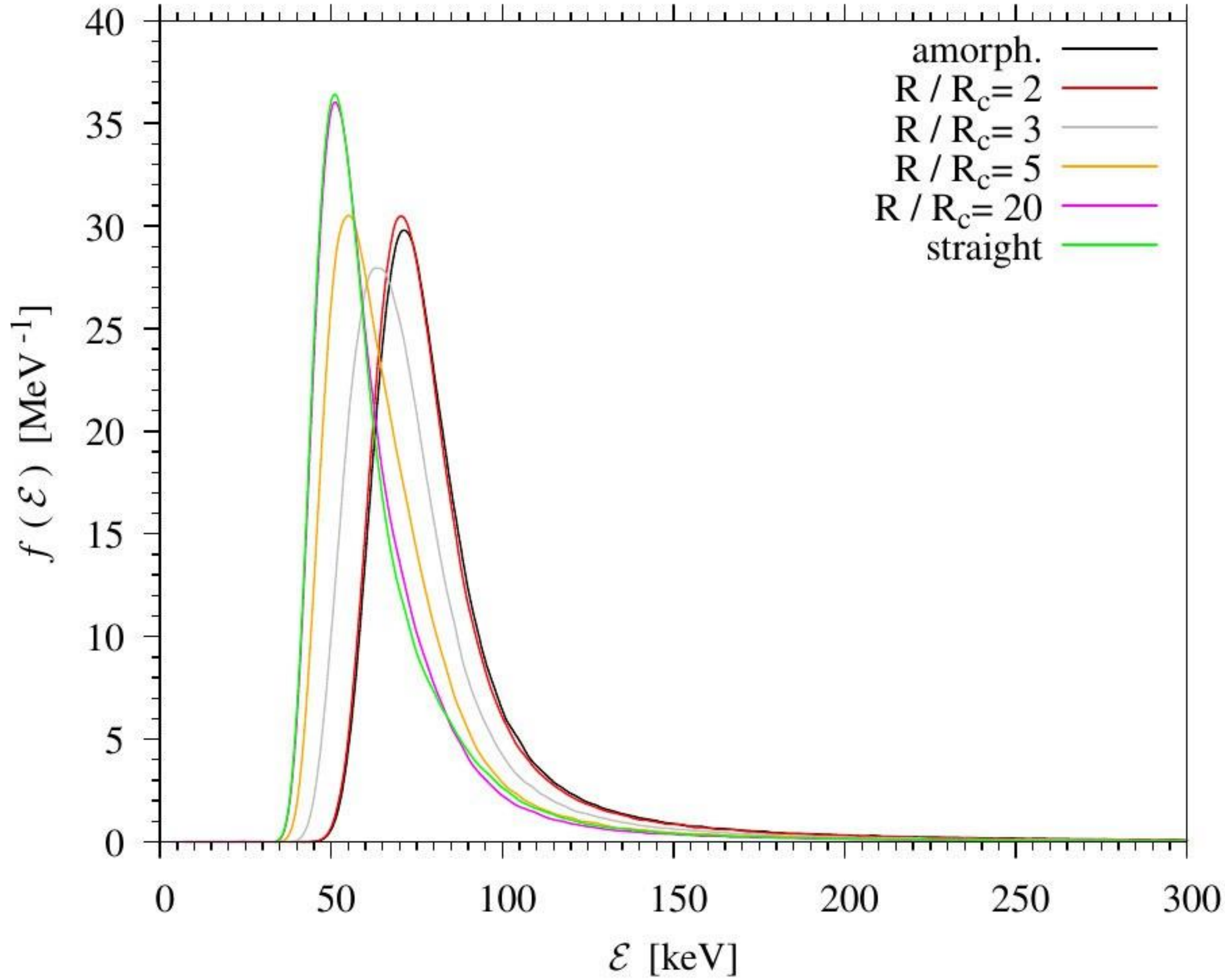
NEGATIVE PARTICLES IN A BENT CRYSTAL

Dependence of the hight of the maximum of ionization loss spectra for 150 GeV π^{-}mesons at planar channeling in (110) planes of L=250 μm Si crystal on the crystal curvature radius



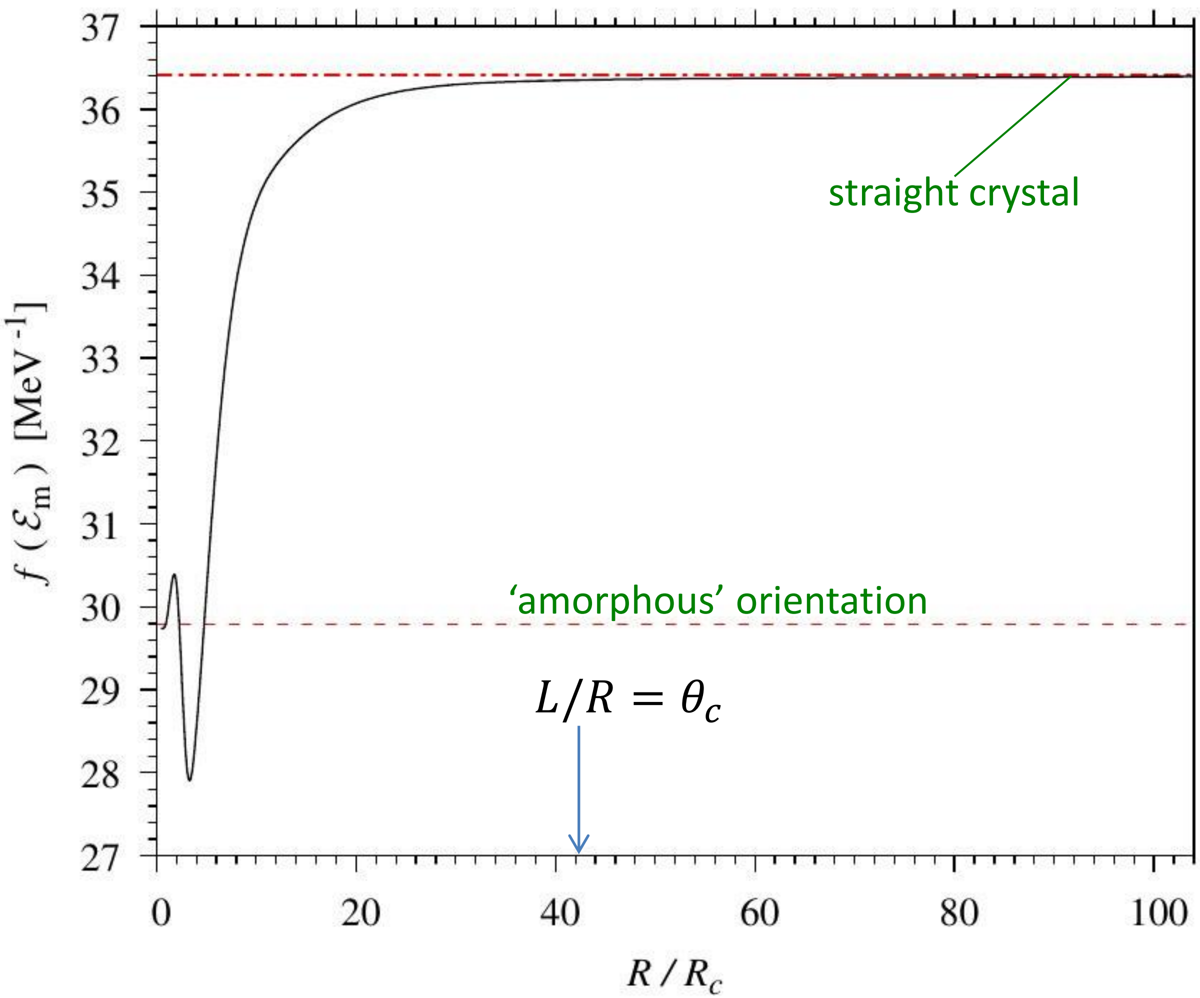
POSITIVE PARTICLES IN A BENT CRYSTAL

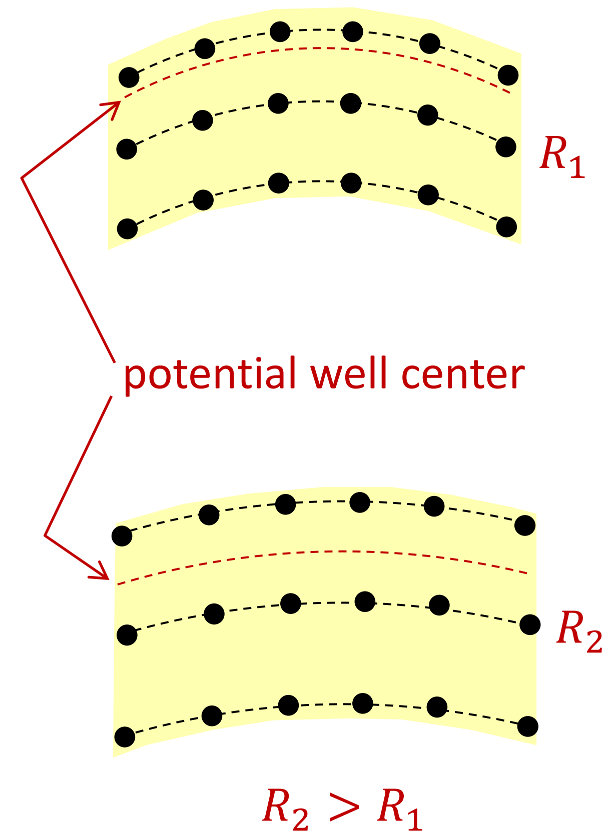
Ionization loss spectra for 150 GeV π^+ mesons at planar channeling in (110) planes of 250 μm Si crystal for different values of the crystal curvature radius



POSITIVE PARTICLES IN A BENT CRYSTAL

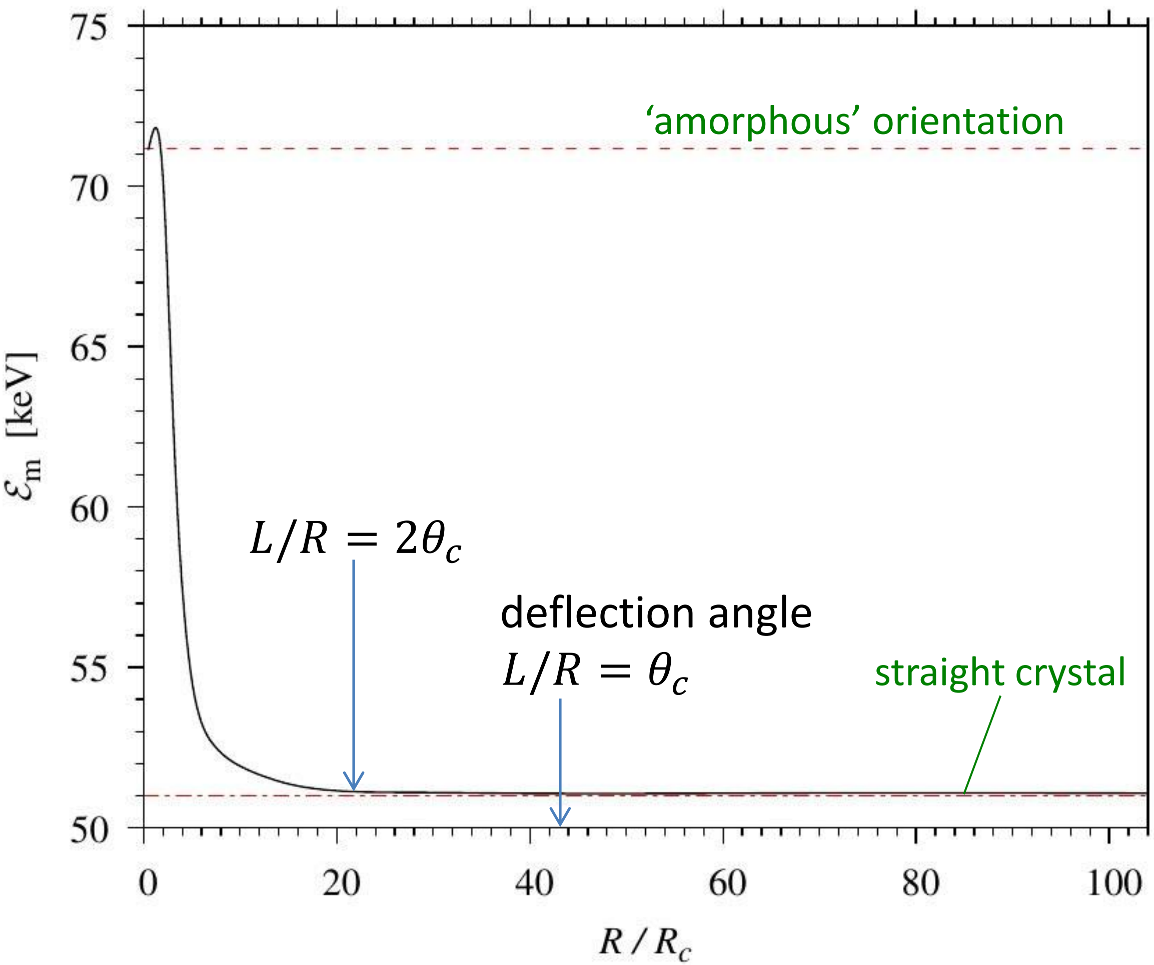
Dependence of the hight of the maximum of ionization loss spectra for 150 GeV π^+ mesons at planar channeling in (110) planes of L=250 μm Si crystal on the crystal curvature radius



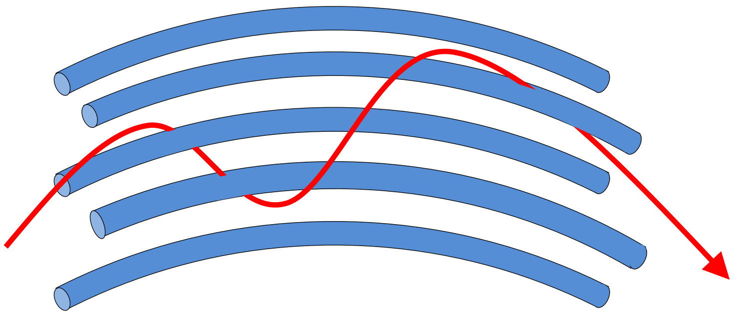


POSITIVE PARTICLES IN A BENT CRYSTAL

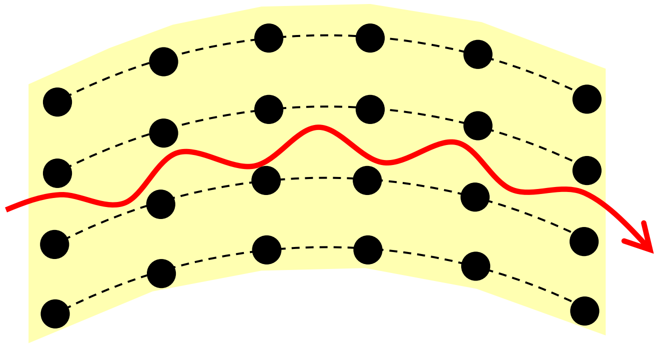
Dependence of the position of the maximum of ionization loss spectra for 150 GeV π^+ mesons at planar channeling in (110) planes of L=250 μm Si crystal on the crystal curvature radius



TASKS FOR THE DFG PROJECT



Investigate ionization loss spectra under conditions of Grinenko-Shul'ga deflection mechanism in a bent crystal for the parameters of DESY II



Investigate ionization loss spectra under conditions of planar channeling for the parameters of DESY II and make a comparative analysis with the spectra under conditions of Grinenko-Shul'ga deflection mechanism

DECHANNELING LENGTH

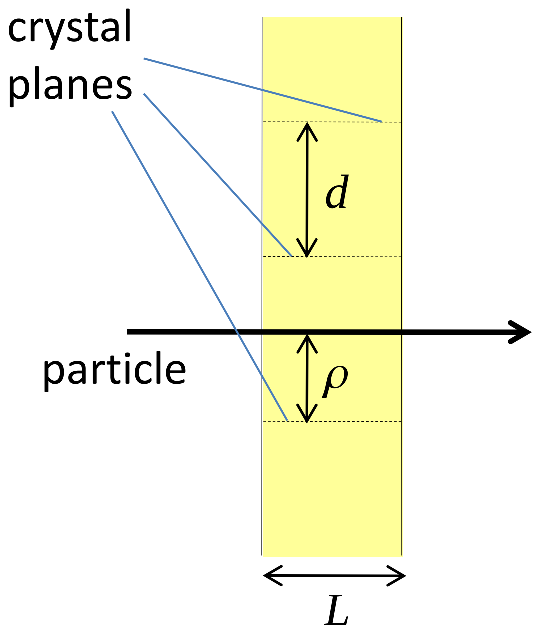
$l_d = \xi E$ – length at which $1/e \approx 0.37$ of particles still remains channeled

Plane	Particles	E(GeV)	ξ (μm/GeV)	Refs.
(110)	e^-		**17.8**	[1]
(110)	e^-	0.855	**21.1**	[2]
(110)	e^-	0.855	**48.0**	[3]
(110)	e^-	0.855	**9.7**	[4]
(110)	e^-	1.2	**24.2**	[5]
(110)	π^-	150	**6.2**	[6]
(111)	e^-		**23.6**	[1]
(111)	e^-	0.855	**23.7**	[7]
(111)	e^-	0.855	**15.9**	[4]
(111)	e^-	3.35-14	**15.3**	[8]
(111)	e^-	0.5-100	**27**	[9]
(111)	e^-	50	**6.6**	[10]

1. V. Baier et al., Electromagnetic Processes at High Energies in Oriented Single Crystals, 1998
2. H. Backe et al., NIMB, 2008
3. W. Lauth et al., Int. J. Mod. Phys. A, 2010
4. A. Kostyuk et al., J. Phys. B,2011
5. V.I. Vit'ko, G.D. Kovalenko, JETP, 1988
6. W. Scandale et al., Phys. Lett. B, 2013
7. A. Mazzolari et al., Phys. Rev. Lett., 2014
8. T.N. Wistisen et al., Phys. Rev. Accel. Beams 2016
9. M. Tabrizi et al., Phys. Rev. Lett., 2007
10. V.M. Biryukov, arXiv:0712.3904, 2007

Large uncertainty in the value of ξ

POSSIBILITY OF l_d DETERMINATION VIA MEASUREMENT OF IONIZATION LOSS SPECTRA



Proposal of the dechanneling length determination from the ionization loss spectra:

S.V. Trofymenko , I.V. Kyryllin, Eur. Phys. J. C, 80 (2020) 689

In the case when $l_d \sim L$ ionization loss spectrum for a single particle:

$$f_1(E,\rho) = l_d^{-1}(\rho)\int_0^L dx e^{-x/l_d(\rho)} \times$$

$$\times \int_0^E f_{\text{ch}}(x,\varepsilon,\rho)\, f_{\text{overbar}}(L-x, E-\varepsilon)\, d\varepsilon$$

Ionization loss spectrum for the whole beam:

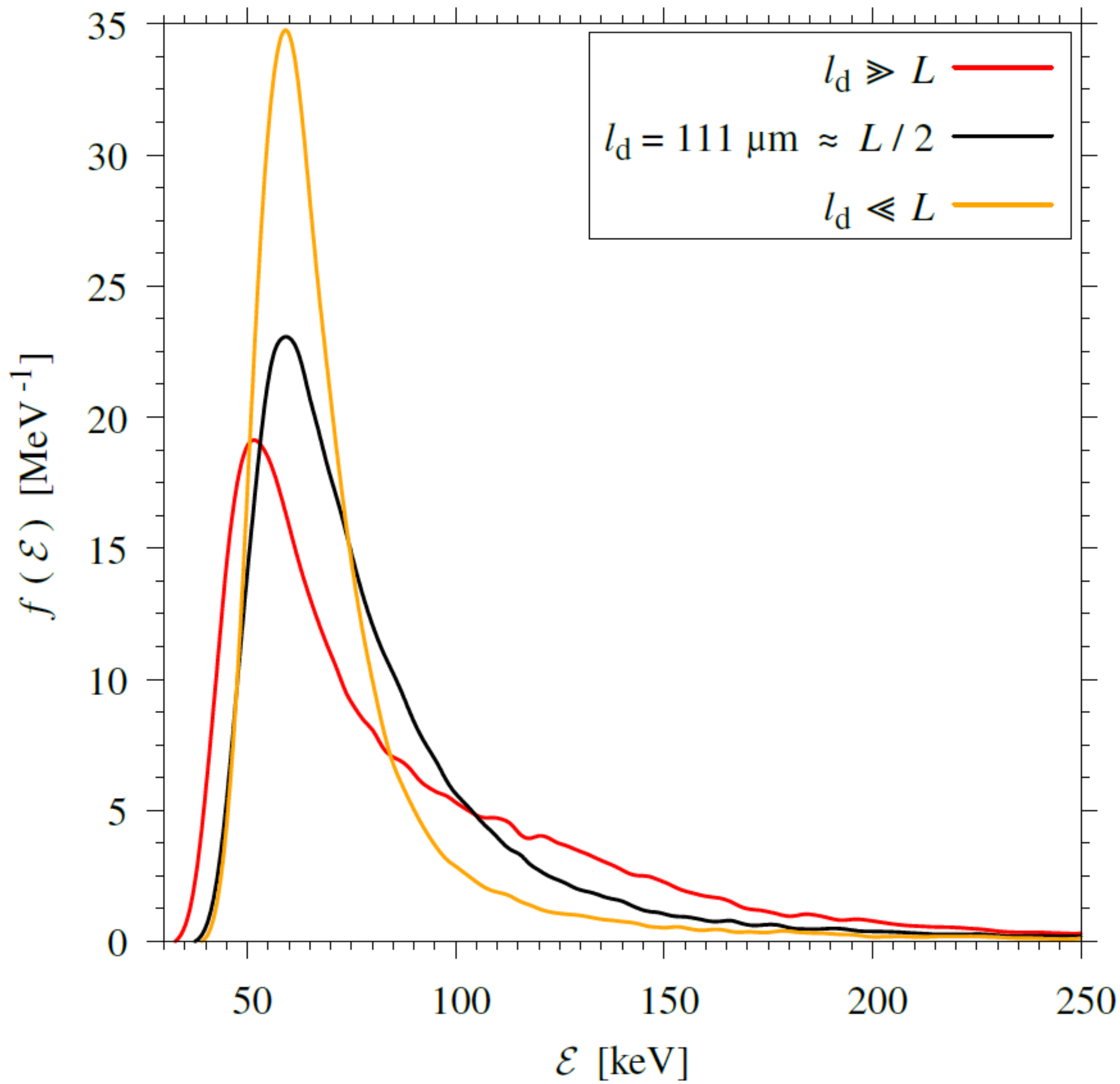
$$l_d = \langle l_d(\rho) \rangle$$

$$f_{\text{beam}}(E) = d^{-1}\int_0^d f_1(E,\rho)\, d\rho$$

Under the condition $l_d \sim L$ ionization loss spectrum is sensitive to the value of l_d

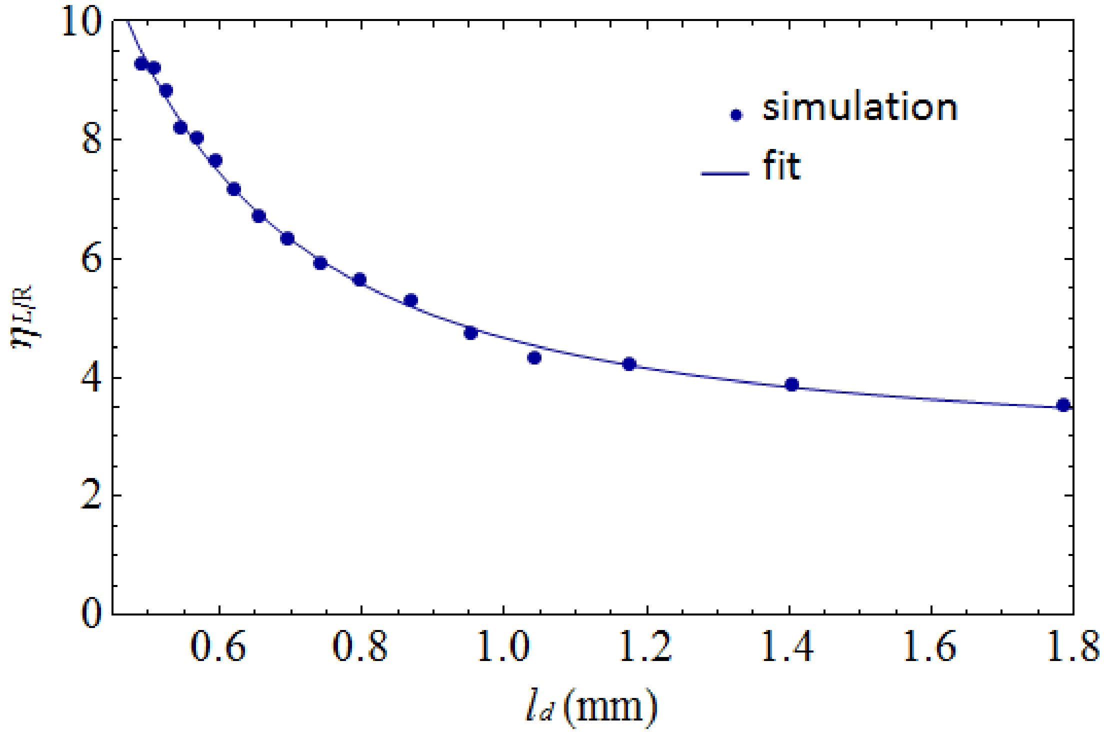
DEPENDENCE OF THE SPECTRUM ON THE DECHANNELING LENGTH

Ionization loss spectra of 15 GeV antiprotons in 220 mm silicon target for different ratio of l_d/L. The particles incident along (110) plane



DEPENDENCE OF THE SPECTRUM ON THE DECHANNELING LENGTH

Dependence of the ratio of the spectrum value at the maximum E_{max} to its value at higher ionization loss $[(2 \div 3)E_{\mathrm{max}}]$
(earlier data from *S.V. Trofymenko , I.V. Kyryllin, Eur. Phys. J. C, 80 (2020) 689*)



It is preferable to apply several targets of different thicknesses $\sim l_d$

Proposal to apply detector with smoothly tunable thickness:
A.V. Shchagin, G. Kube, S.A. Strokov, W. Lauth, NIM A 1059 (2024) 168930

Task for the DFG project: investigate feasibility of the proposed method of the dechanneling length measurement for the parameters of MAMI

CONCLUSIONS

- The method of simulation of the ionization loss spectra in oriented crystals is elaborated

- Orientation dependences for the ionization loss spectra of 15 GeV protons in straight silicon crystals are obtained

- The evolution of the most probable E_{MP} and average E_{AV} ionization loss values at the transitions *planar* → *'amorphous'* and *axial* → *planar* orientation, is investigated

- The ionization loss spectra have been simulated in bent crystals for very high particle energies

- The developed techniques are planned to be applied for investigation of the ionization loss spectra in conditions of Grinenko-Shul'ga and planar channeling deflection mechanisms in bent crystals for the parameters of DESY II

- For the target thickness $L \sim l_d$ the shape of the ionization loss spectrum is sensitive to the dechanneling length value l_d, which is proposed to apply for the measurement of l_d. Feasibility of this method is planned to be investigated for the parameters of MAMI