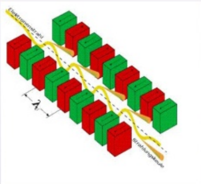
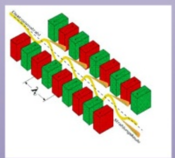
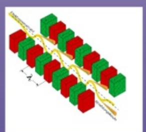






Crystal Undulators: from the Prediction to the Mature Simulations

Vladimir Baryshevsky & Victor Tikhomirov
Research Institute for Nuclear Problems, Minsk, Belarus

Channeling 2012 Alghero September 27

Plan

CU radiation prediction and ultimate
perspectives of its application

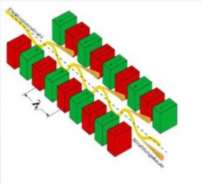
CU radiation simulation

experiments with electrons

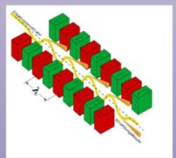
predictions for positrons

CU radiation improvement
by crystal cut

Plan



CU radiation prediction and ultimate perspectives of its application



CU radiation simulation

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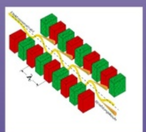
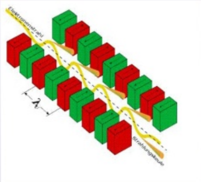


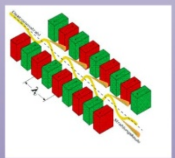
CU radiation improvement

by crystal cut

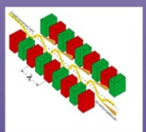


The prediction of Radiation in Crystal Undulators:

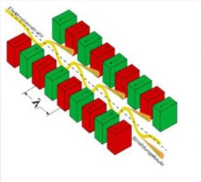
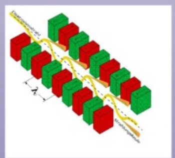
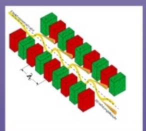
Baryshevsky V.G., Grubich A.O., Dubovskaya I. Ya.
*Phys. Lett. A77(**1980**)61.*



Voroviev S.A., Kaplin V.V., Plotnikov S.V.
*Zh. Tekh. Fiz. 50(**1980**)1079.*



Crystal plane undulations can be exerted by either ***ultrasonic*** or ***laser wave***

X-ray laser on channeling needs $j \geq 10^{13} A/cm^2$

Baryshevsky V.G., Feranchuk I.D.

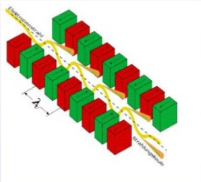
*Phys. Lett. A102(**1984**)141.*

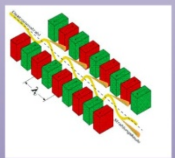
Baier V.N., Milstein A.I.

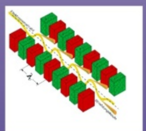
*NIM B17(**1986**)25.*

Bazylev V.A., Zhevago N.K.

*Fast Particle Radiation in Matter and External Fields, **1987**.*



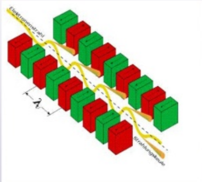


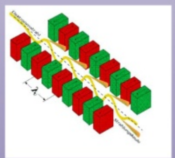


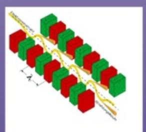
γ-ray laser threshold current can be reduced to j ≥ **10^8A/cm^2** using distributed feedback provided by ***x-ray diffraction***

Baryshevsky V.G., Feranchuk I.D.

*Phys. Lett. A102(**1984**)141.*

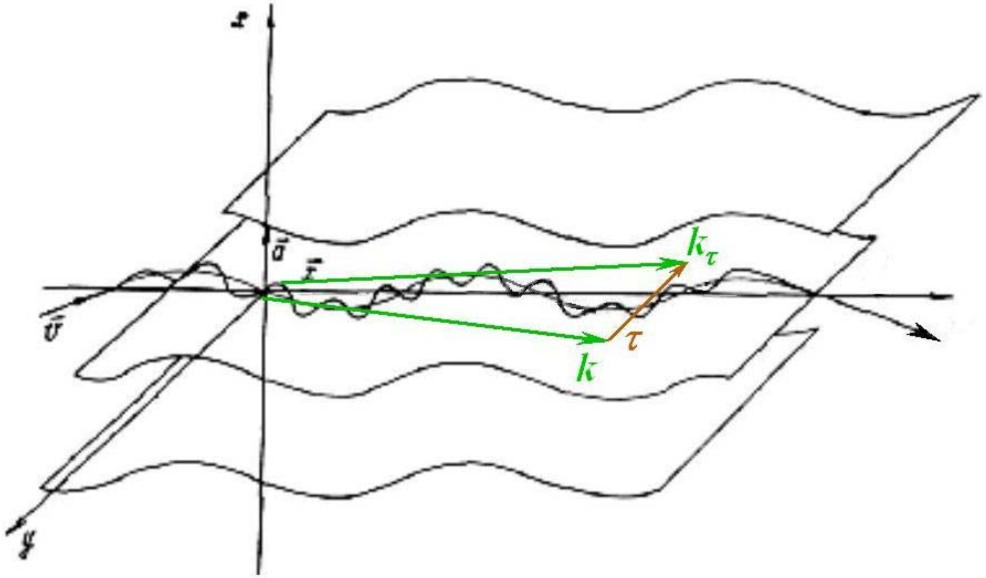






Diffraction Radiation in Crystal Undulator

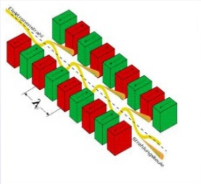
Baryshevsky V.G., Dubovskaya I. Ya. J. Phys. CM. 33*(**1991**)*2421.

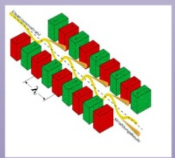


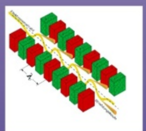
$$N^{s}_{\tau m} = [\pi Q^2 \sqrt{\beta_1} L |g^{s}_{\tau}(\omega_B)|^2 \omega_B^2 m^2 / 16 |\tau_z|] \times a^2 \Omega'^2 [1 - 2(\omega_B/\omega_{max}) + 4P^{s}_{\tau}(\omega_B/\omega_{max})^2]. \quad (22)$$

– is ***more intensive*** than the

Diffraction Radiation of Channeled Particles







Crystal Undulator radiation

used with distributed feedback

provided by *x-ray diffraction*

open up a real perspective

of ***γ-laser*** development

Plan

CU radiation prediction and ultimate perspective of its application

CU radiation simulation

experiments with electrons

predictions for positrons

CU radiation improvement by crystal cut

We proceed from the genuine formula of *Baier* and *Katkov*

The general expression for radiation intensity

$$\frac{d^2 I}{d\omega d^2\theta} = \frac{\alpha\omega^2 d\omega}{8\pi^2\varepsilon'^2} \times \int\int dt_1 dt_2 \left[(\varepsilon^2 + \varepsilon'^2)(\mathbf{v}_\perp(t_1) - \boldsymbol{\theta})(\mathbf{v}_\perp(t_2) - \boldsymbol{\theta}) + \omega^2/\gamma^2\right]$$

$$\exp\left\{ i\frac{\omega\varepsilon}{2\varepsilon'} \left[\int_{-\infty}^{t_1} \left(\gamma^{-2} + (\mathbf{v}_\perp(t') - \boldsymbol{\theta})^2\right) dt' + \int_{-\infty}^{t_2} \left(\gamma^{-2} + (\mathbf{v}_\perp(t'') - \boldsymbol{\theta})^2\right) dt'' \right] \right\}$$

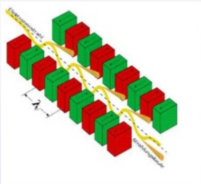
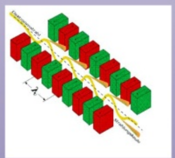
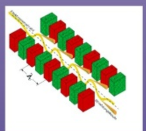
contains two integrals

$$A = \int \exp\left\{ i\frac{\omega\varepsilon}{2\varepsilon'} \int_{-\infty}^{t} \left[\gamma^{-2} + (\mathbf{v}_\perp(t') - \boldsymbol{\theta})^2\right] dt' \right\} dt,$$

$$\mathbf{B} = \int (\mathbf{v}_\perp(t) - \boldsymbol{\theta}) \exp\left\{ i\frac{\omega\varepsilon}{2\varepsilon'} \int_{-\infty}^{t} \left[\gamma^{-2} + (\mathbf{v}_\perp(t') - \boldsymbol{\theta})^2\right] dt' \right\} dt$$

and slowly decreases with radiation angle $\boldsymbol{\theta}$, complicating its numerical integration.

Key simulation points:

Trajectory simulations in most **realistic potentials**

Simulation of **incoherent scattering** on both nuclei and electrons

Separate simulation of **single** and **multiple** scattering

Direct integration of **Baier-Katkov formula**

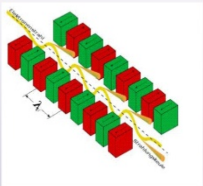
Infinite trajectories, **density** effect…

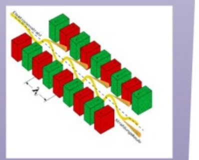
Electron radiation in CU

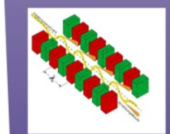
is essentially determined

by the influence

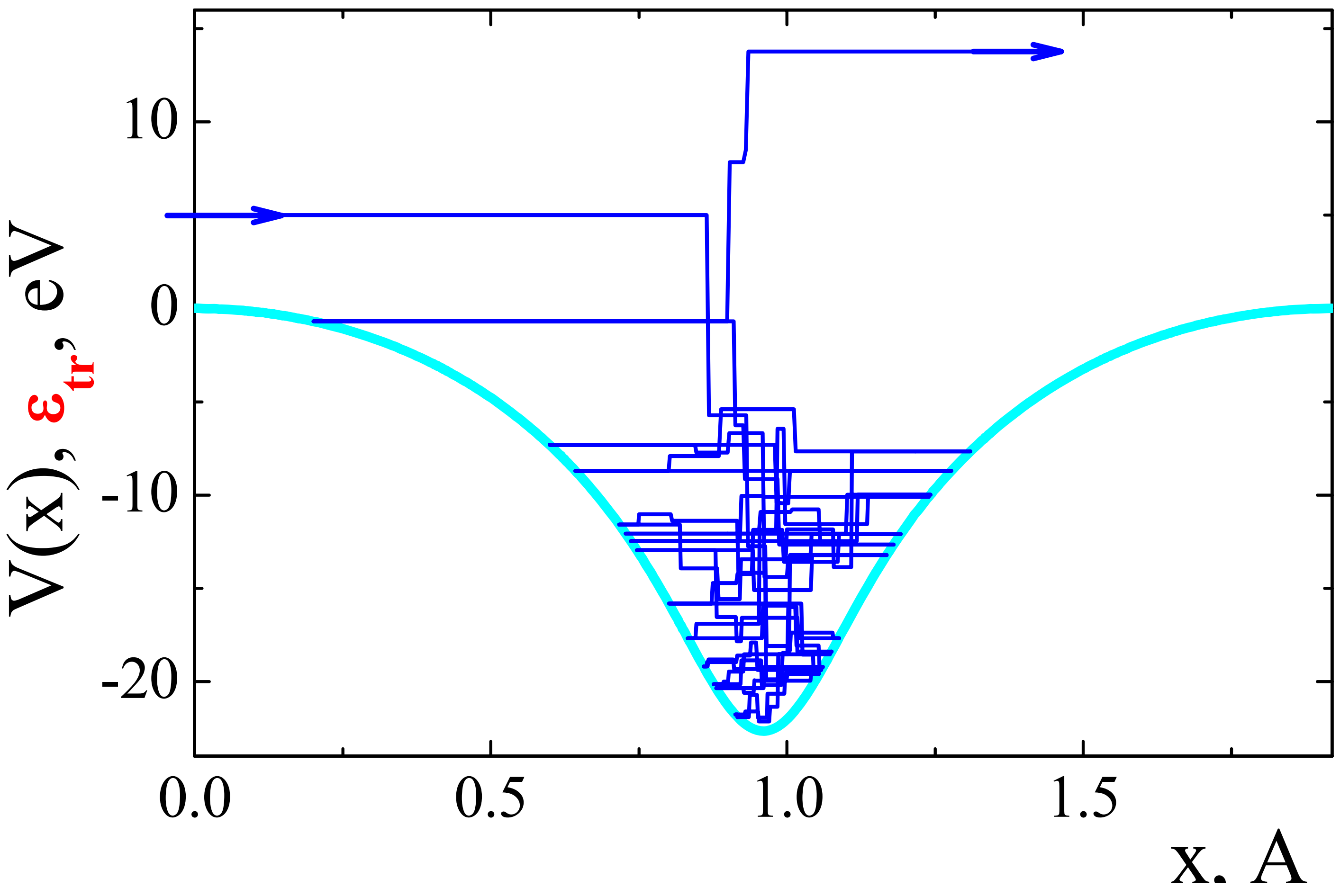
of *incoherent scattering*







Capture of a 287 MeV electron



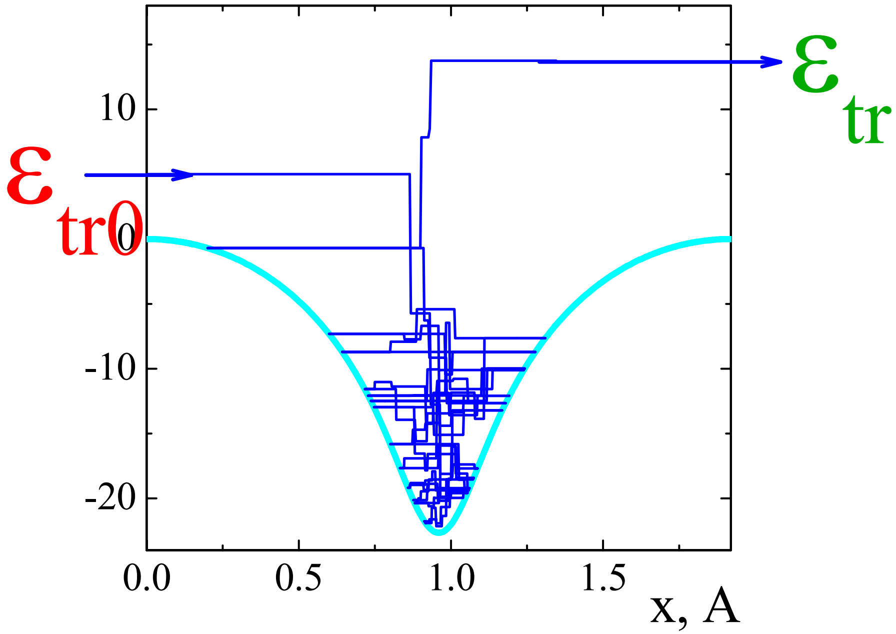
We use below

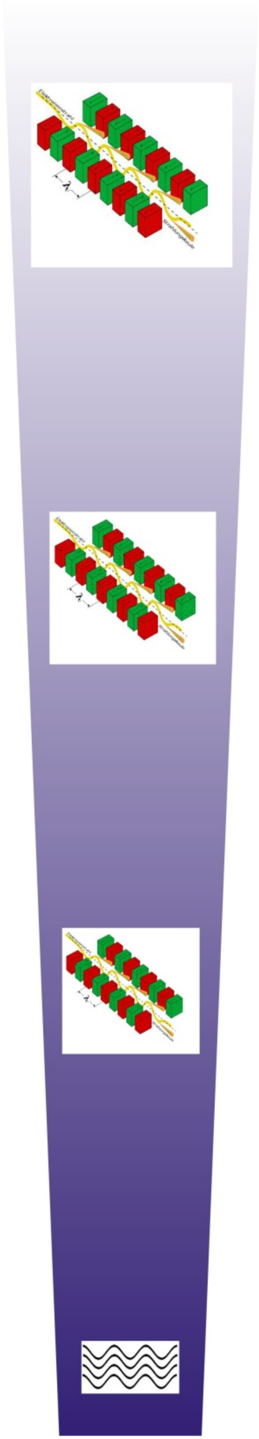
ε_{tr} – energy *of transverse particle motion*

ε_{tr0} – initial ——————//——————

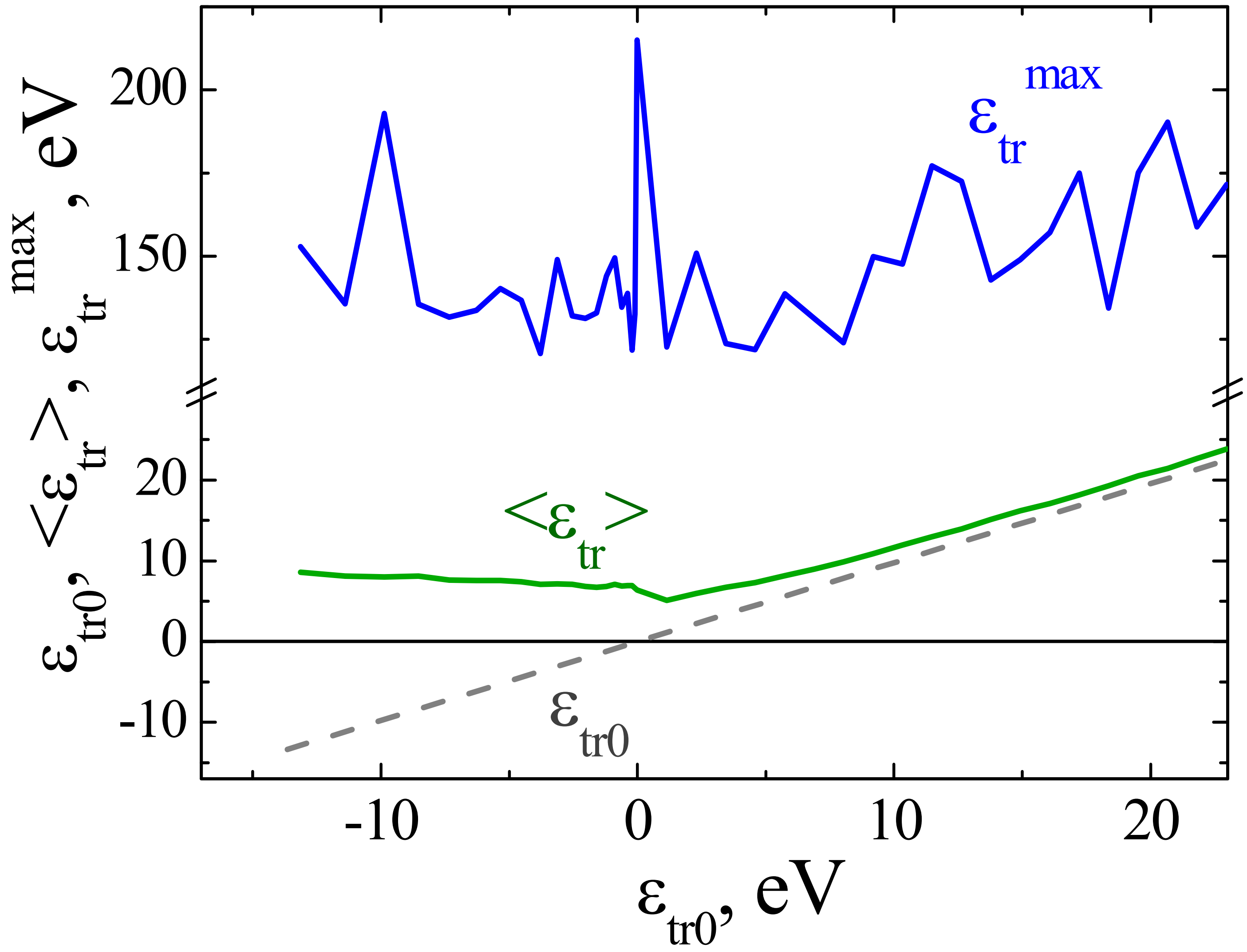
$\langle\varepsilon_{tr}\rangle$ – average ——————//——————

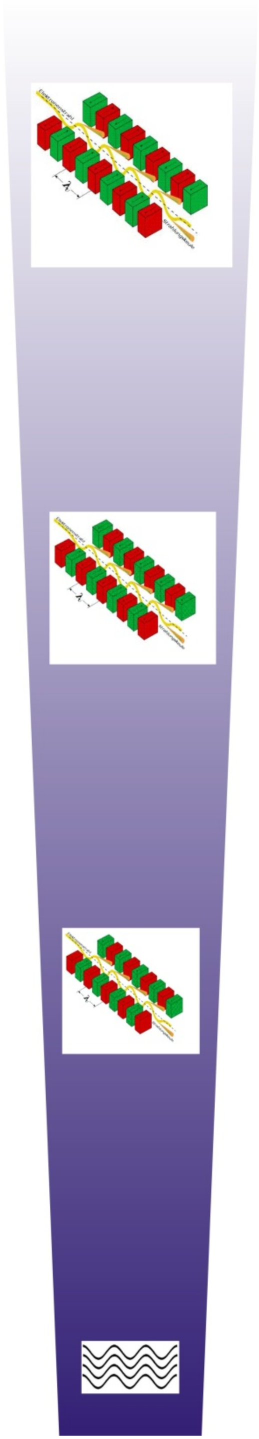
ε_{tr}^{max} – maximal ——————//——————



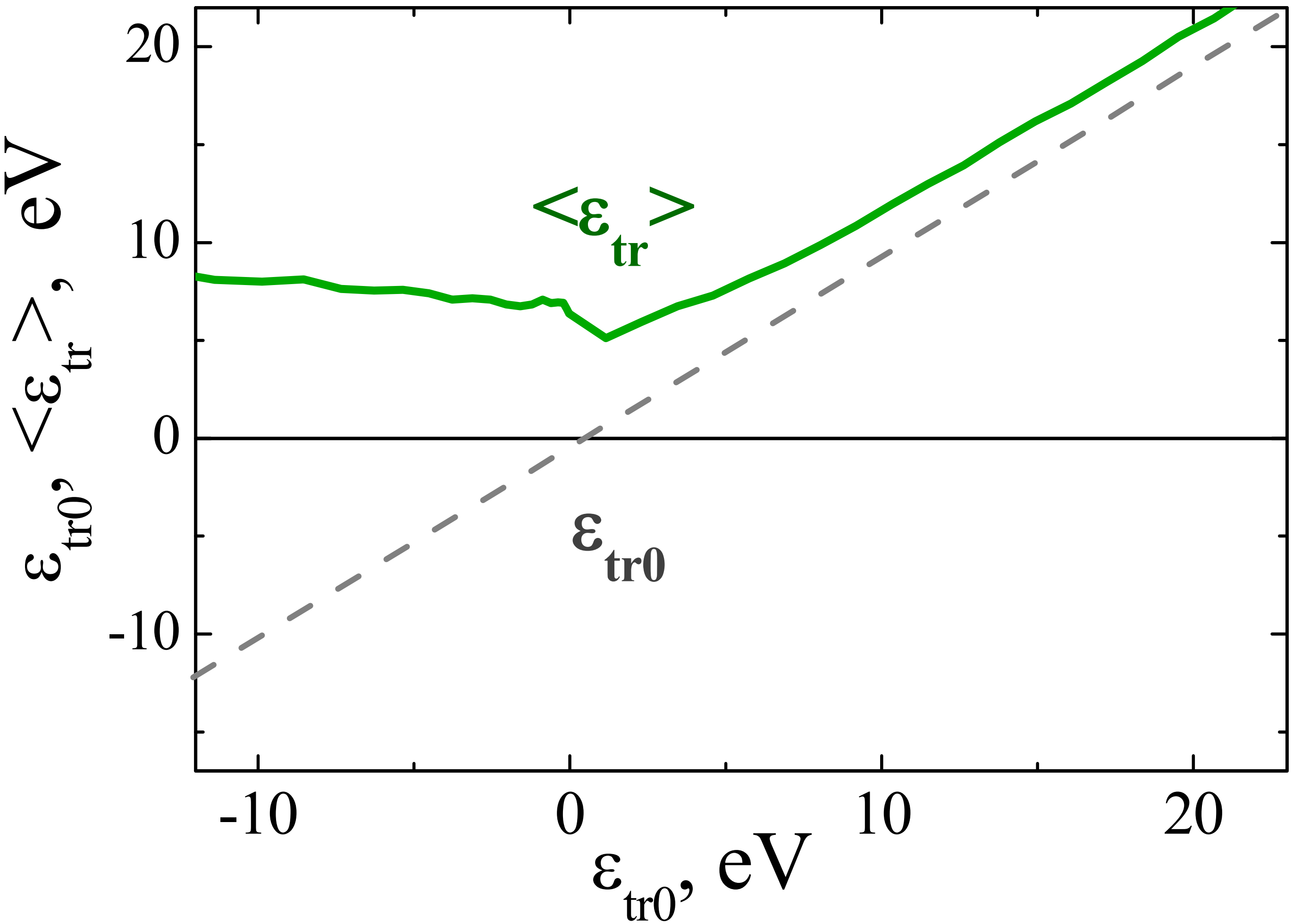


Average and maximum transverse energies

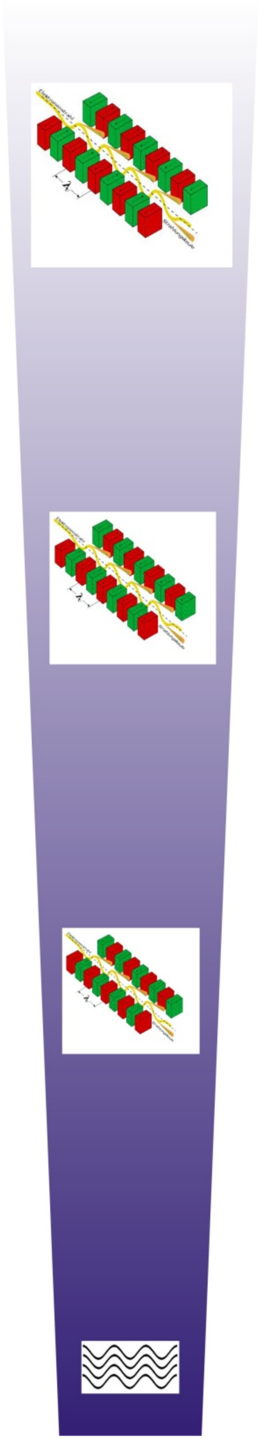


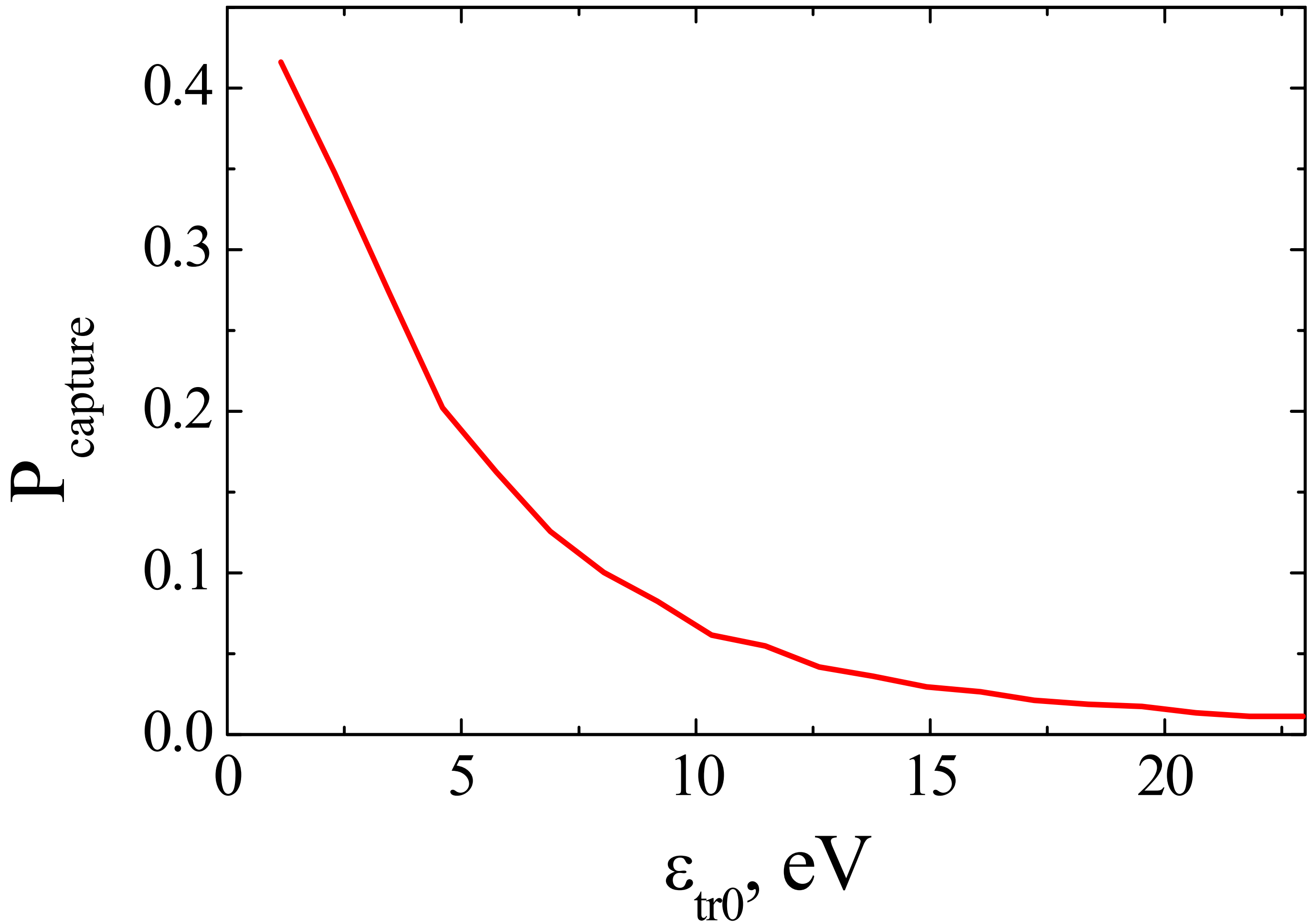


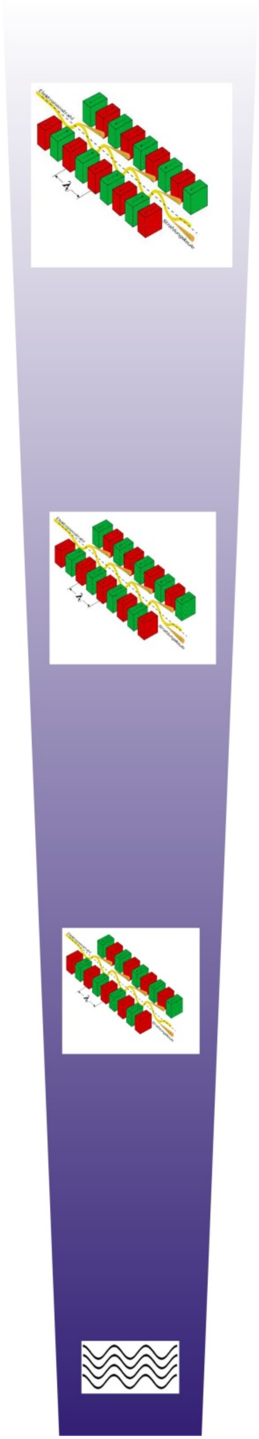
Average and maximum transverse energies



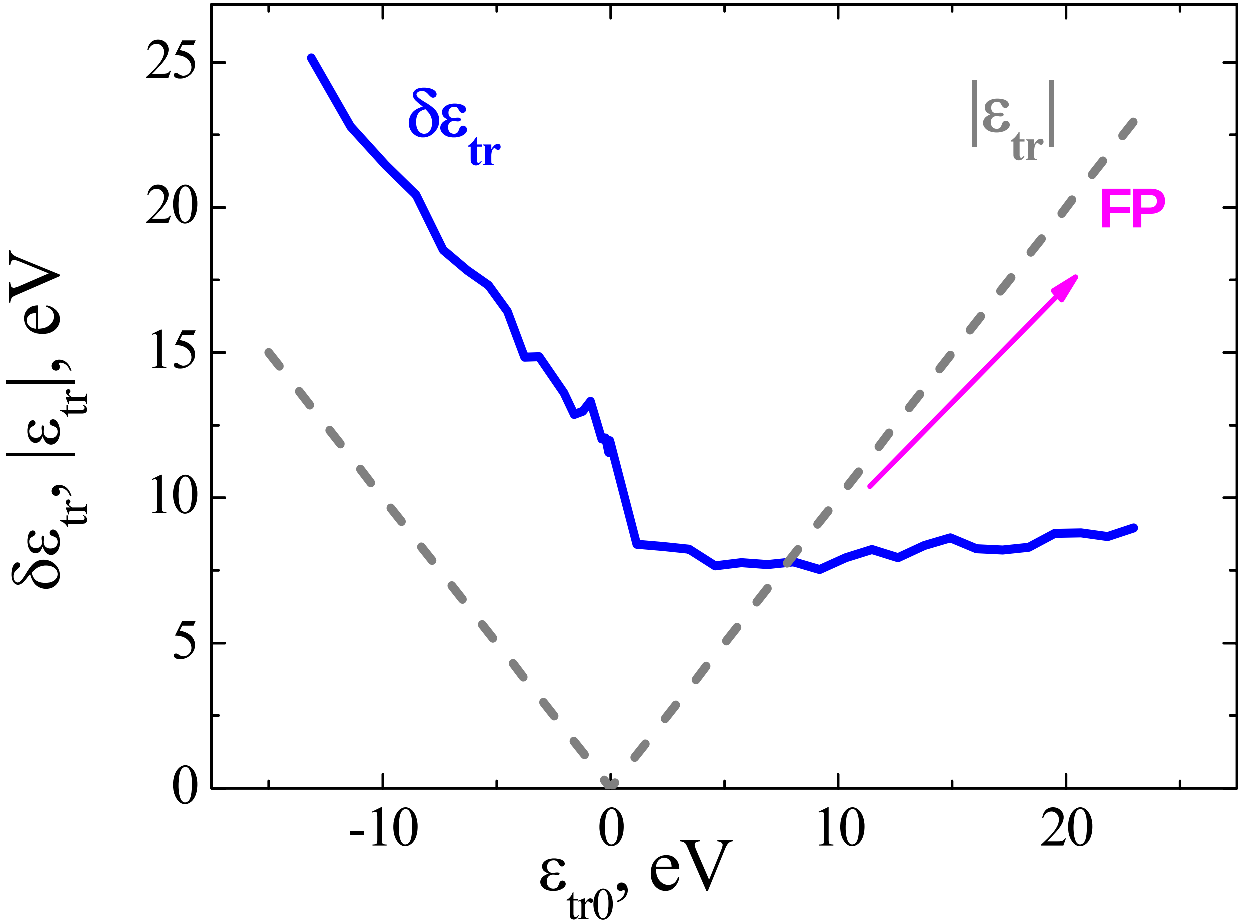
Probability of ***immediate*** capture of 287 MeV protons



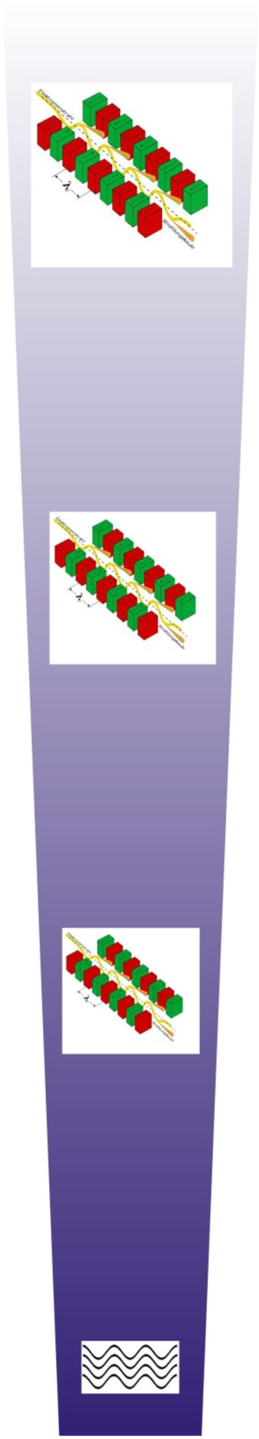


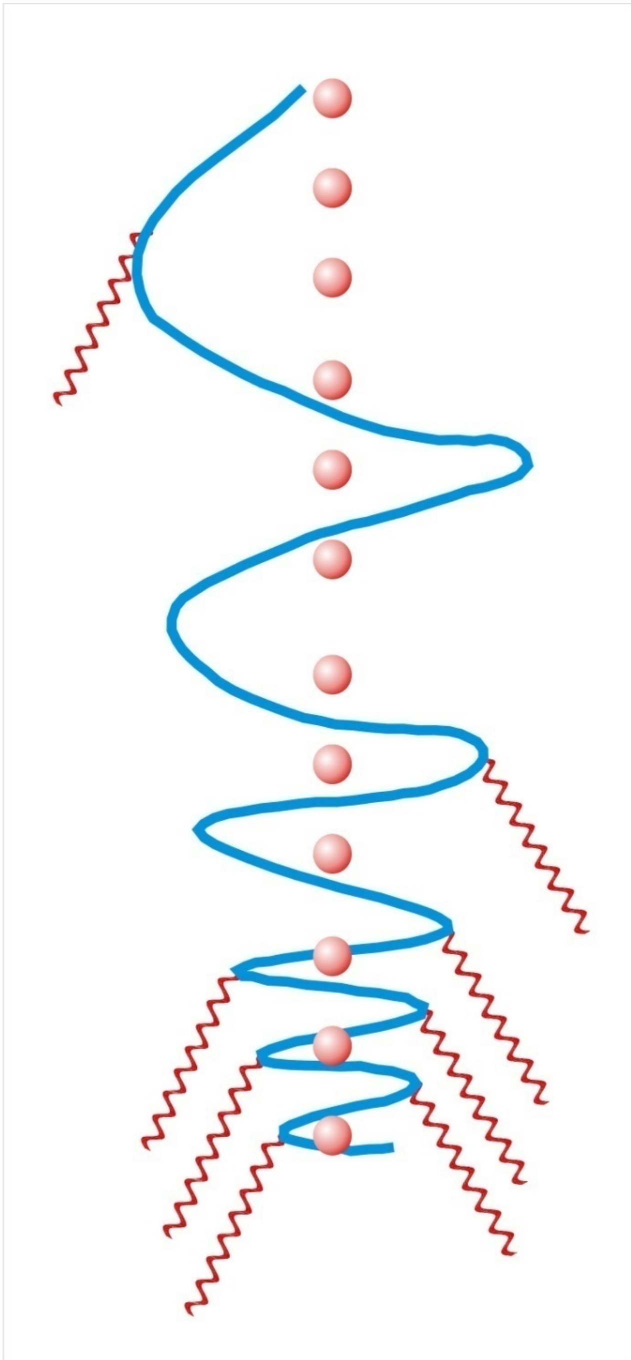


Transverse energy gains large dispersion

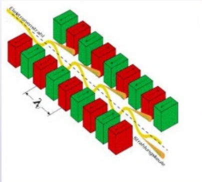


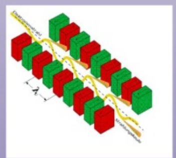
Fokker-Planck equation has very limited applicability

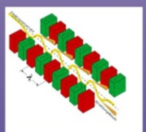




Lessons of ***radiative cooling*** studies work after ***25 years***!







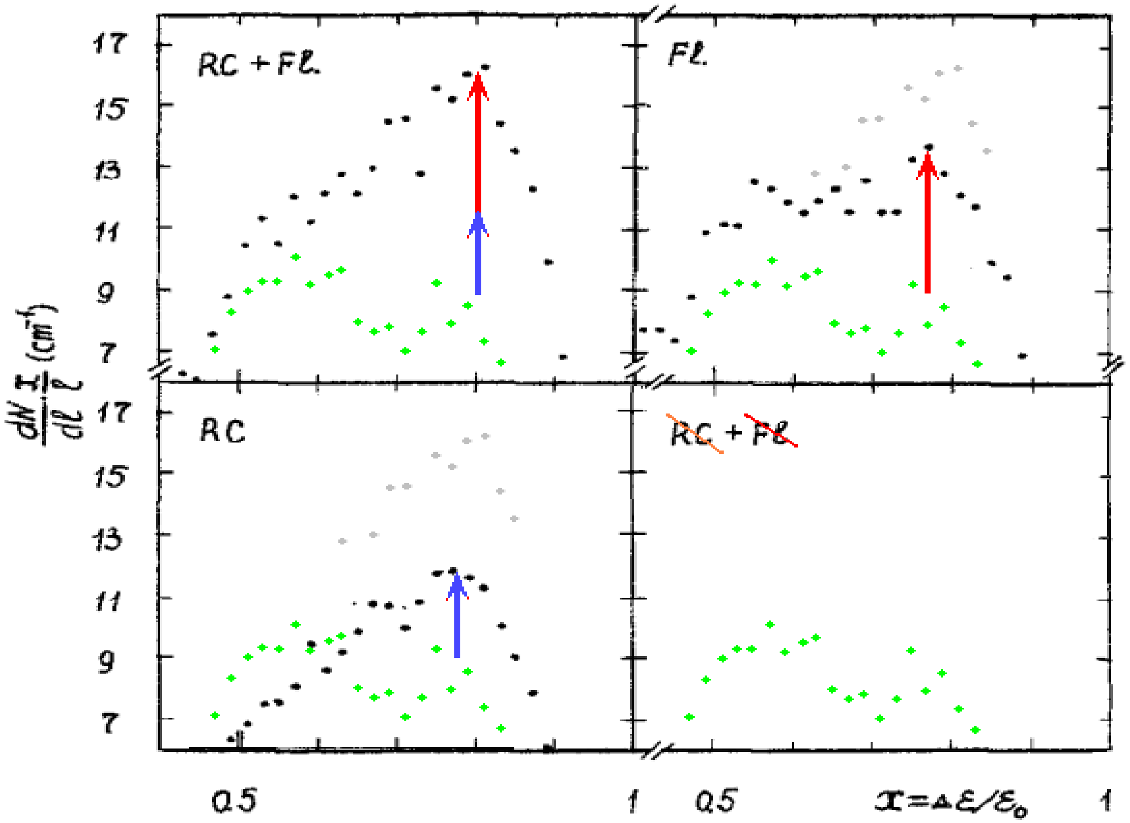
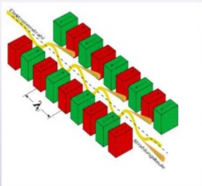
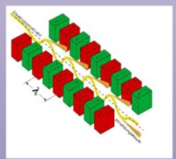
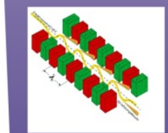


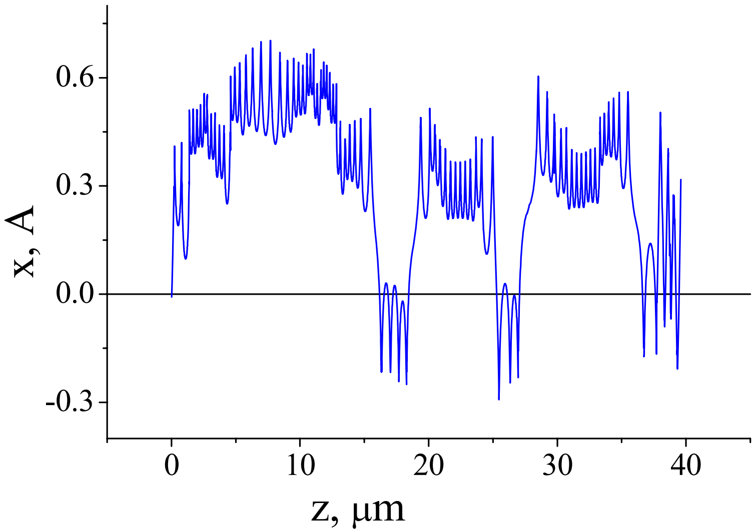
Fig. 2. Simulated energy loss spectra formed by e^- which emit only sufficiently hard γ-quanta with the energies satisfying the inequality (15) under the experimental conditions of ref. [1]. (a) Both the radiation cooling (RC) and $\epsilon_\perp$ fluctuations (FL) are allowed for; (b) the radiation cooling, respectively (c) the $\epsilon_\perp$ fluctuations are neglected; (d) both processes are neglected.

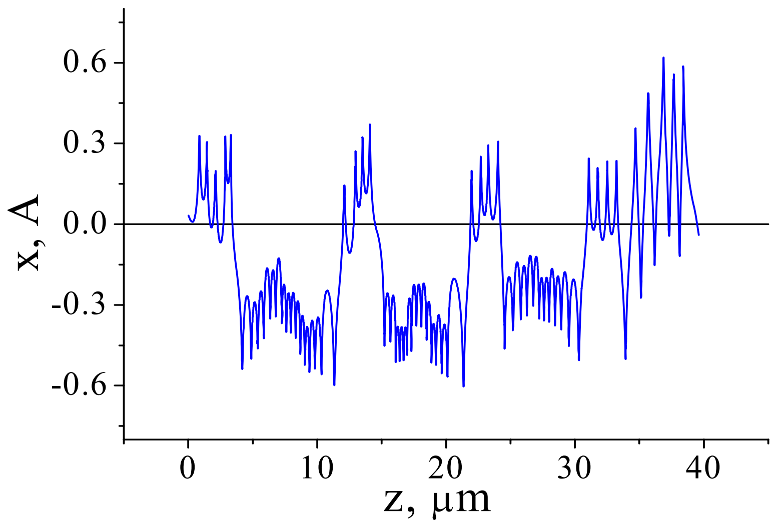






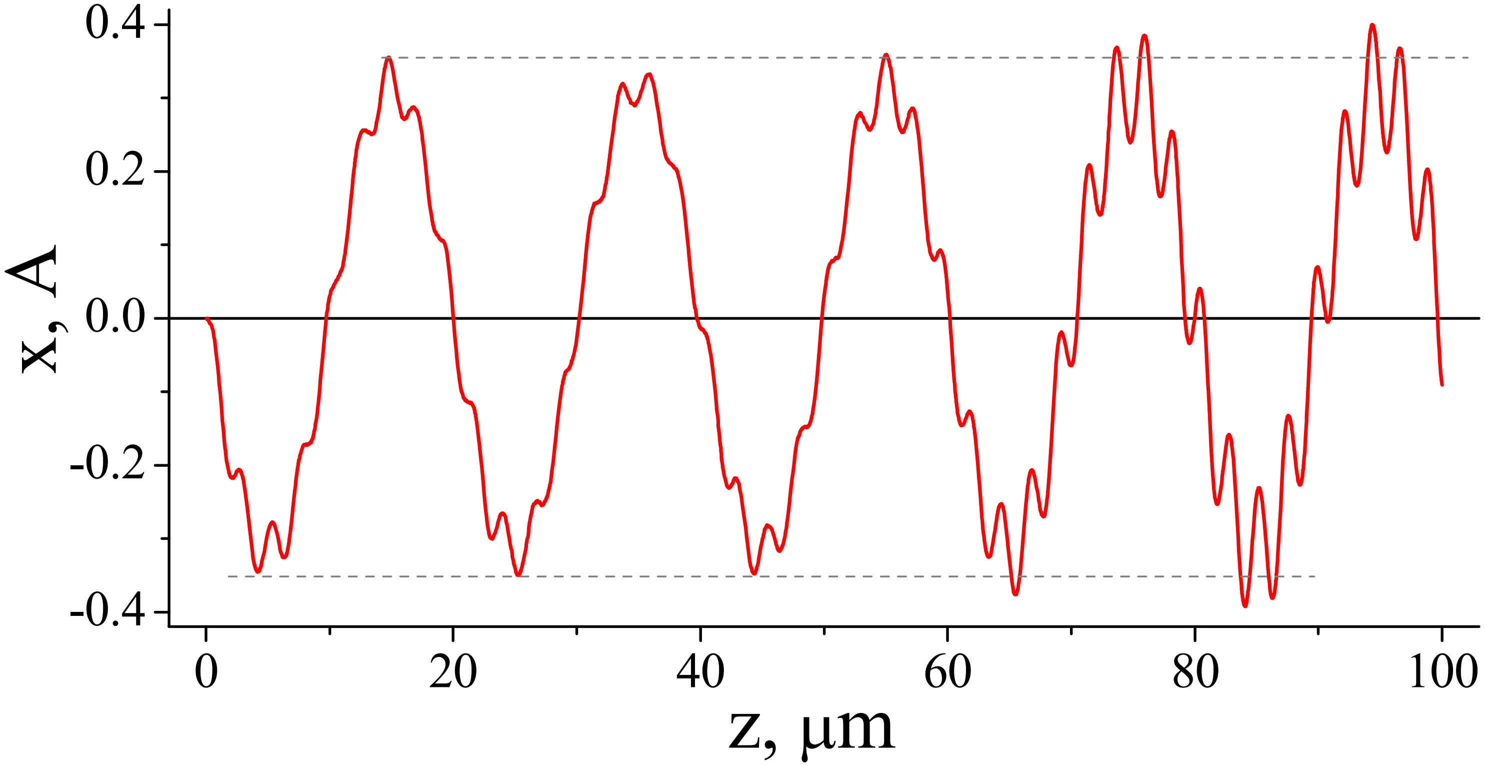
Trajectories of 270 MeV electrons in the 40=4x10um CU

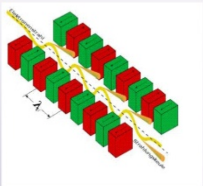


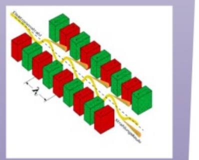


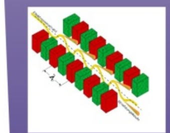
Electrons become channeled several times for short parts of the period

A "*fortunate*" 500 MeV positron trajectory

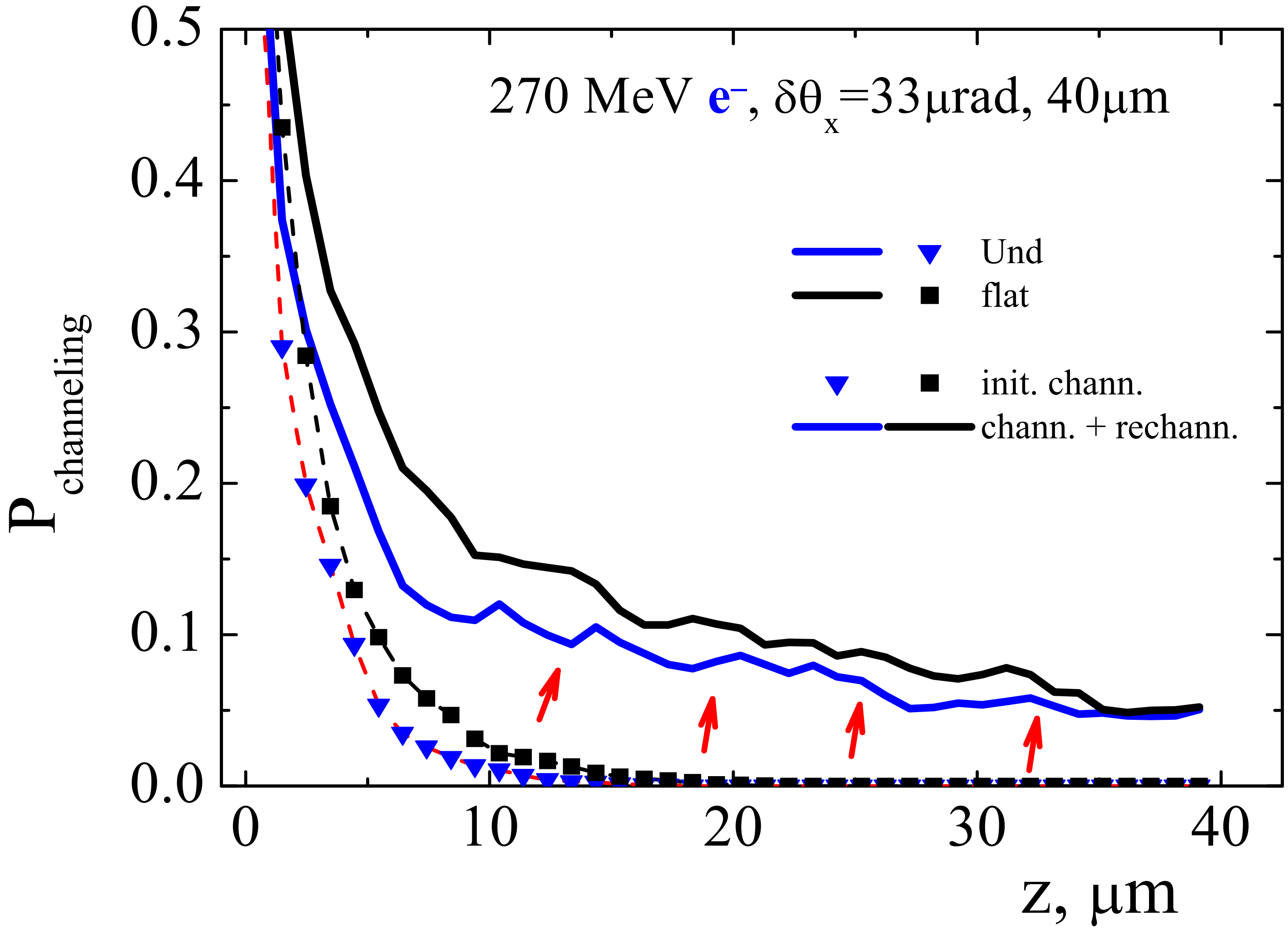








The role of RECHANNELING is enormous



Radiation process simulations from the *“First Principles”*

The general expression for radiation intensity

$$\frac{d^2 I}{d\omega d^2\theta} = \frac{\alpha\omega^2 d\omega}{8\pi^2\varepsilon'^2} \times \int\int dt_1 dt_2 \left[(\varepsilon^2+\varepsilon'^2)(\mathbf{v}_\perp(t_1)-\boldsymbol{\theta})(\mathbf{v}_\perp(t_2)-\boldsymbol{\theta}) + \omega^2/\gamma^2\right]$$

$$\exp\left\{i\frac{\omega\varepsilon}{2\varepsilon'}\left[\int_{-\infty}^{t_1}\left(\gamma^{-2}+(\mathbf{v}_\perp(t')-\boldsymbol{\theta})^2\right)dt' + \int_{-\infty}^{t_2}\left(\gamma^{-2}+(\mathbf{v}_\perp(t'')-\boldsymbol{\theta})^2\right)dt''\right]\right\}$$

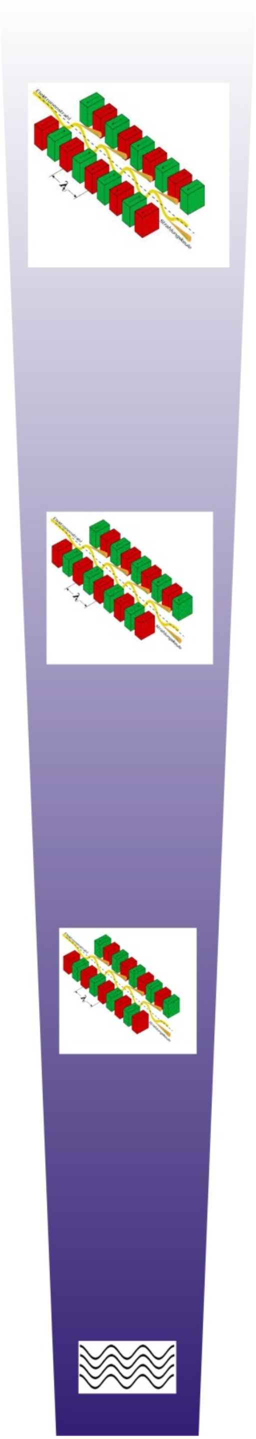
contains two integrals

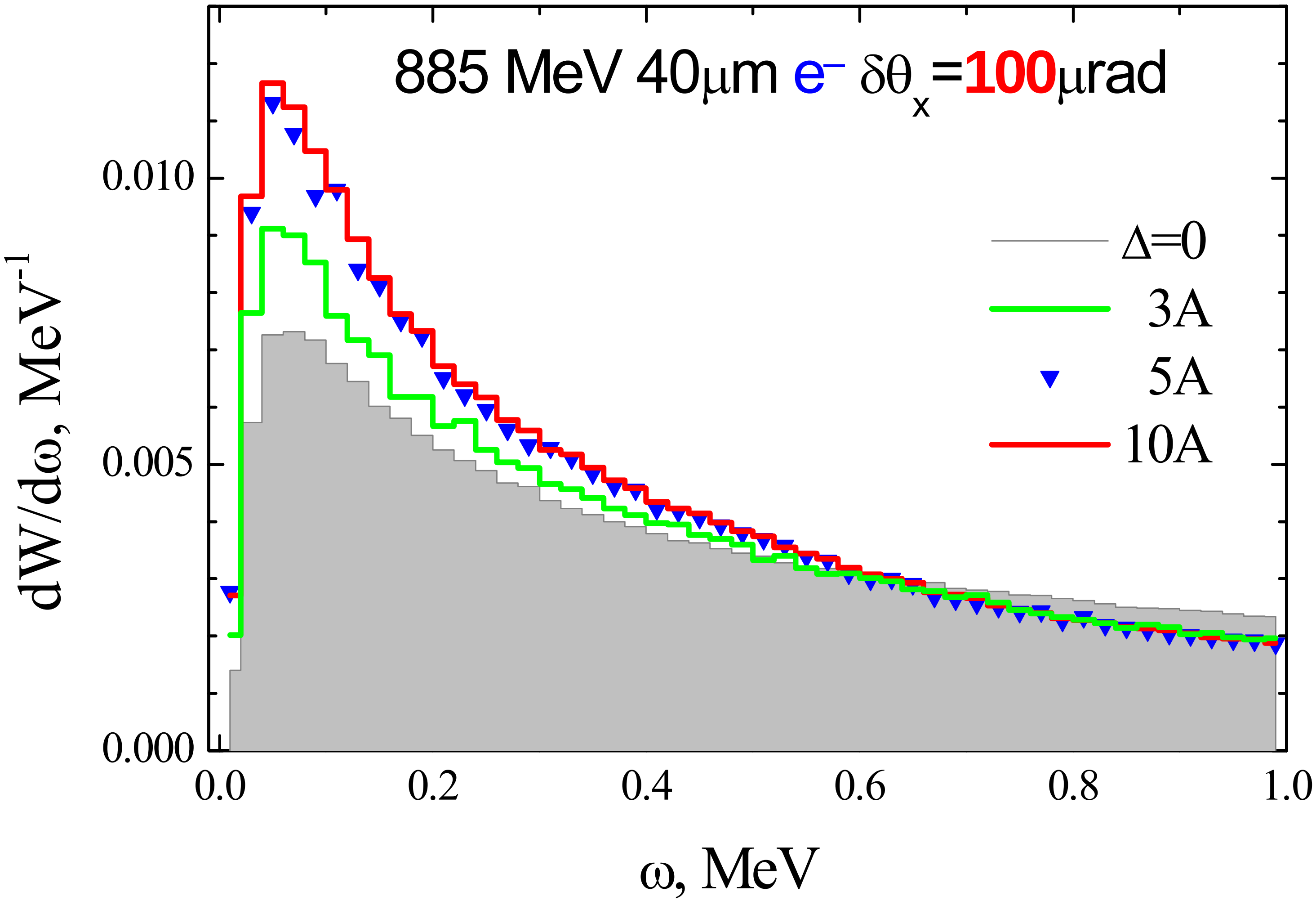
$$A = \int \exp\left\{i\frac{\omega\varepsilon}{2\varepsilon'}\int_{-\infty}^{t}\left[\gamma^{-2}+(\mathbf{v}_\perp(t')-\boldsymbol{\theta})^2\right]dt'\right\}dt,$$

$$\mathbf{B} = \int (\mathbf{v}_\perp(t)-\boldsymbol{\theta})\exp\left\{i\frac{\omega\varepsilon}{2\varepsilon'}\int_{-\infty}^{t}\left[\gamma^{-2}+(\mathbf{v}_\perp(t')-\boldsymbol{\theta})^2\right]dt'\right\}dt$$

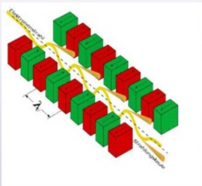
and slowly decreases with radiation angle $\boldsymbol{\theta}$, complicating its numerical integration.

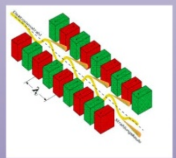
CU intensity dependence on CU modulation amplitude

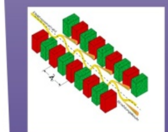




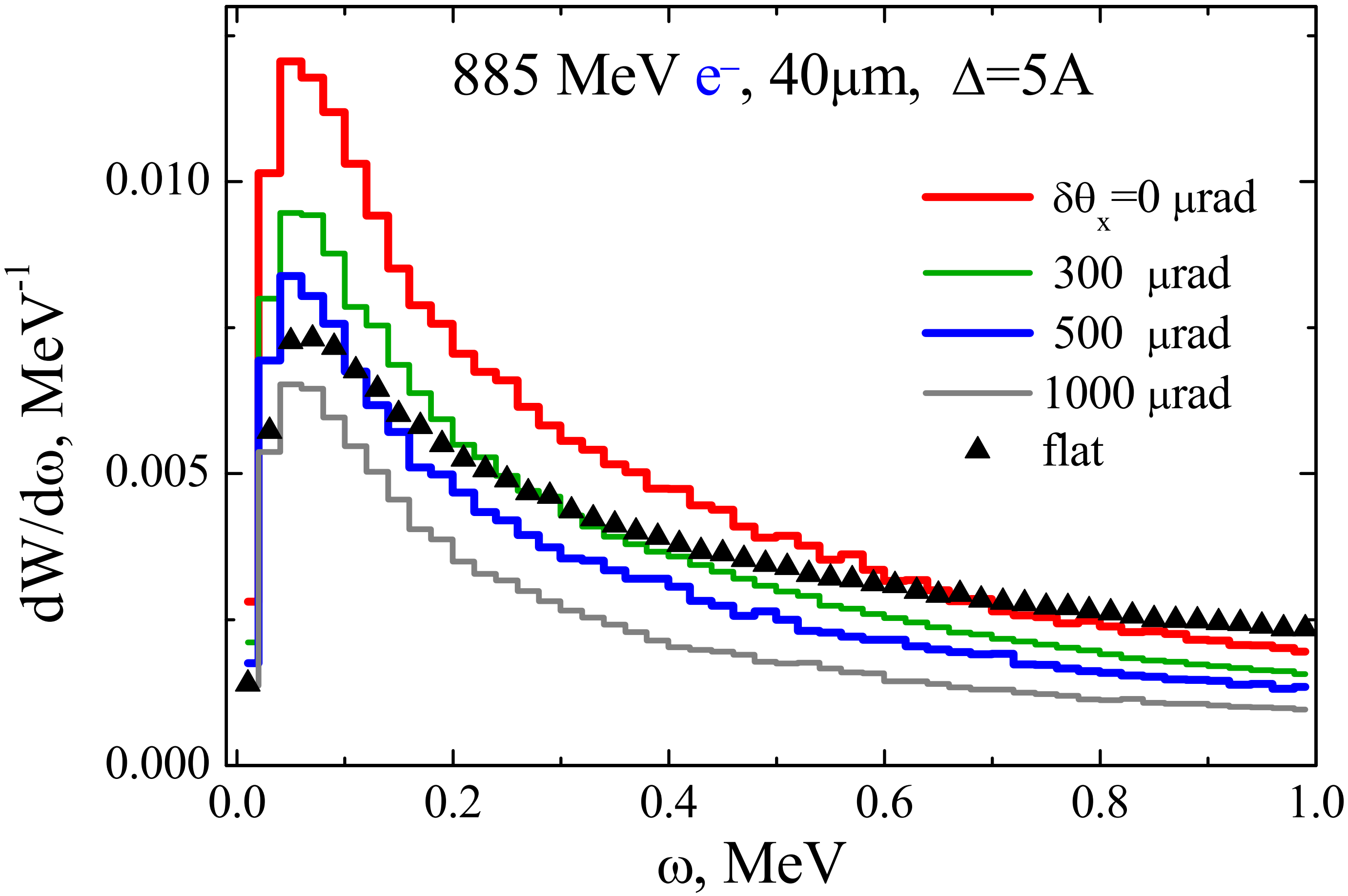
Optimal modulation amplitude is about **5 Angstroms**



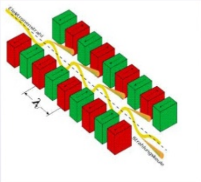


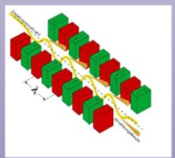


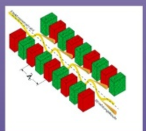
CU intensity dependence on beam divergence



Optimal beam divergence is about **100 μrad**







Plan

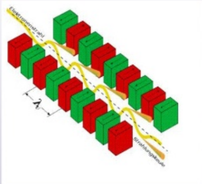
CU radiation prediction and ultimate perspective of its application

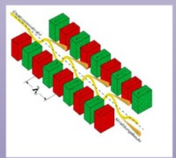
CU radiation simulation

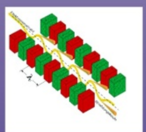
experiments with electrons

predictions for positrons

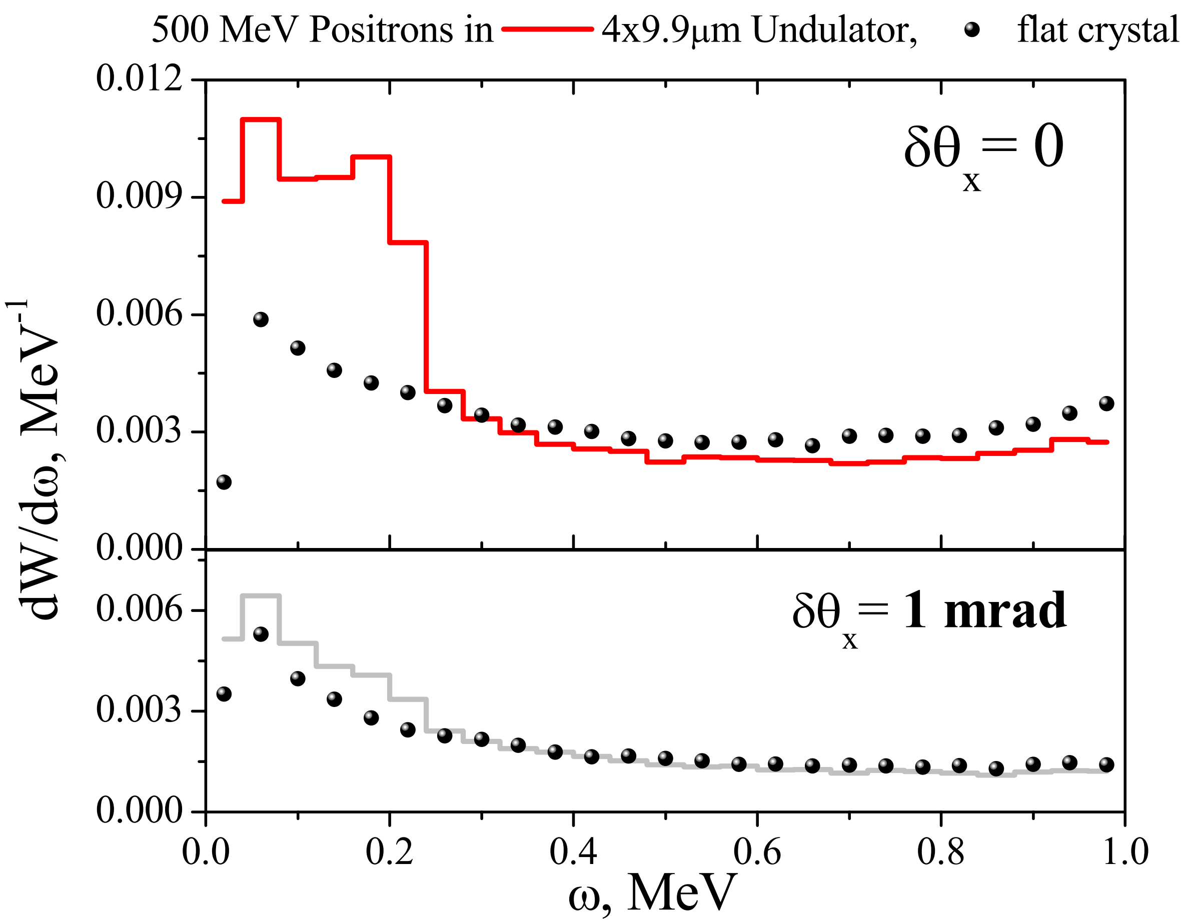
CU radiation improvement by crystal cut





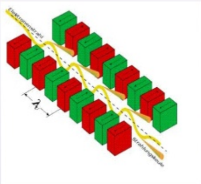


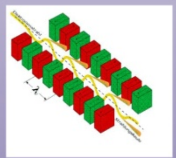
Positron CU radiation

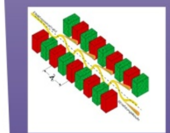


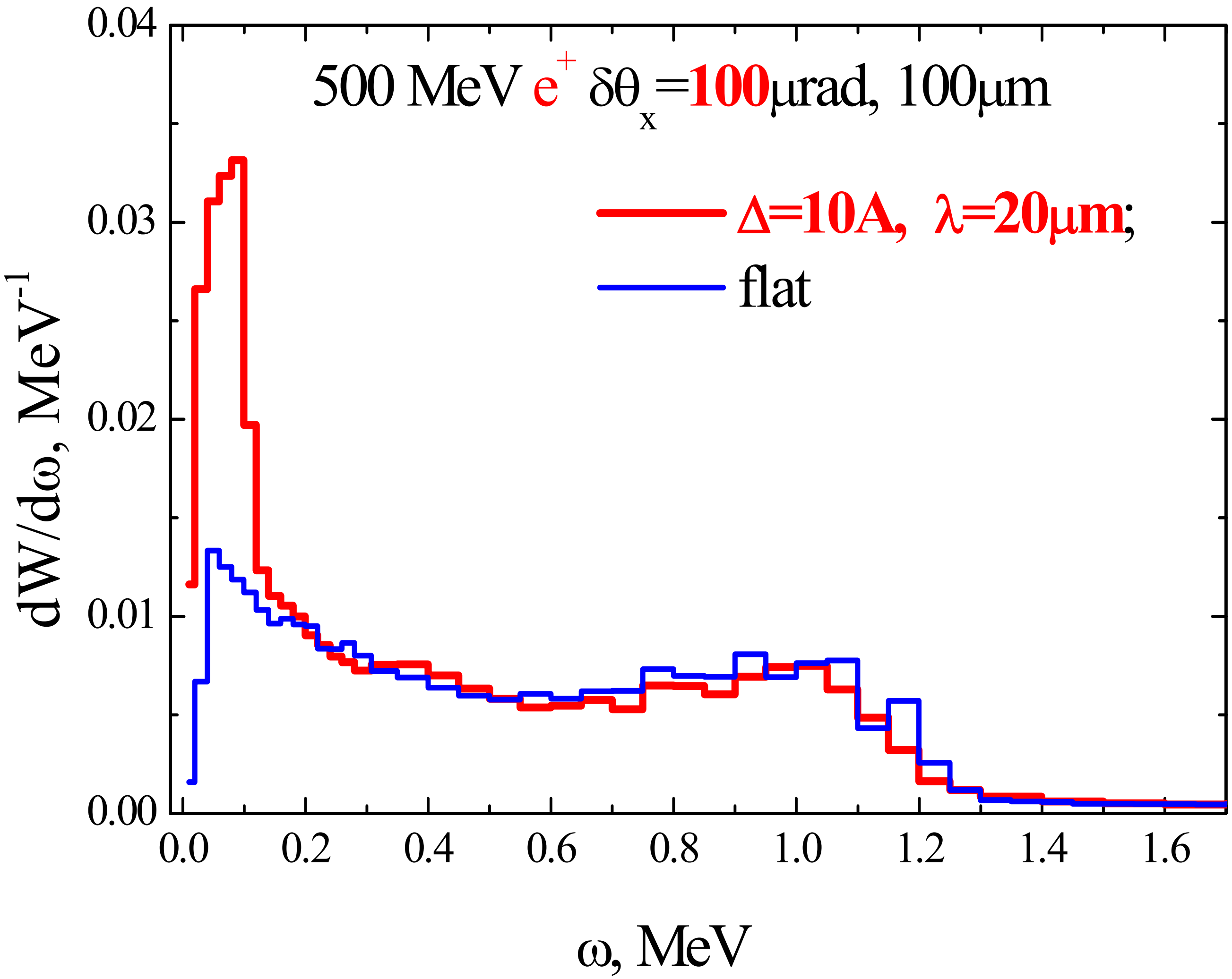
Positron CU radiation have good perspectives

Radiation in more effective CU

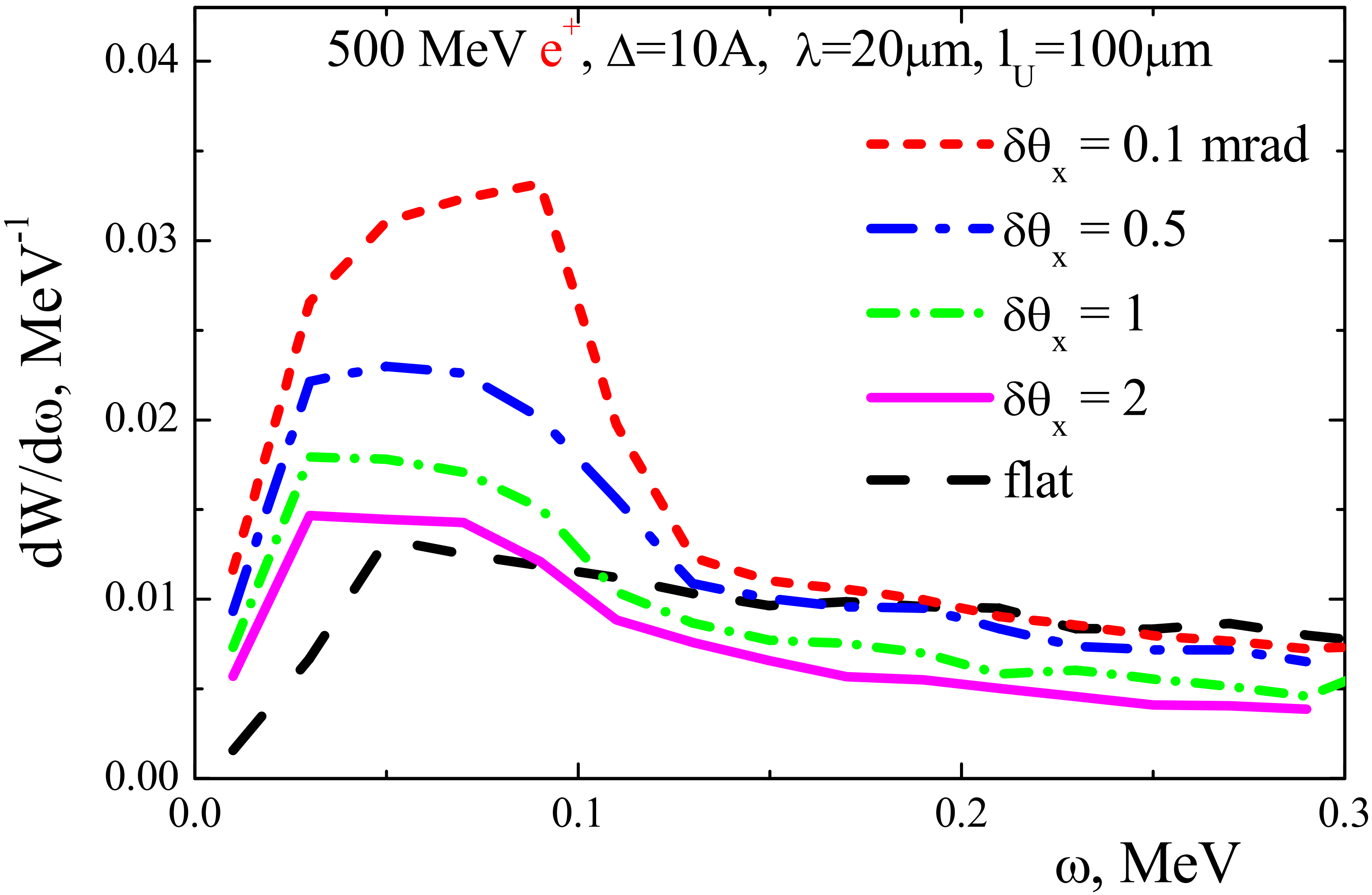








CU intensity dependence on beam divergence



Positron beam divergence can be in **milliradian range**

Plan

CU radiation prediction and ultimate perspective of its application

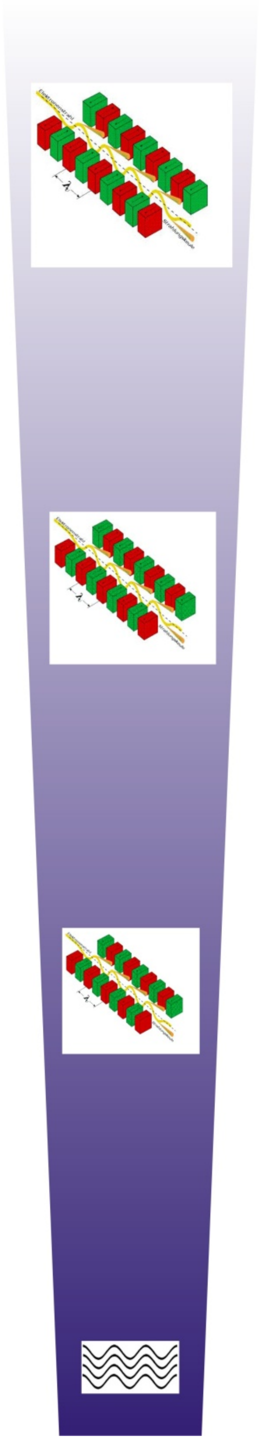
CU radiation simulation

experiments with electrons

predictions for positrons

CU radiation improvement by crystal cut

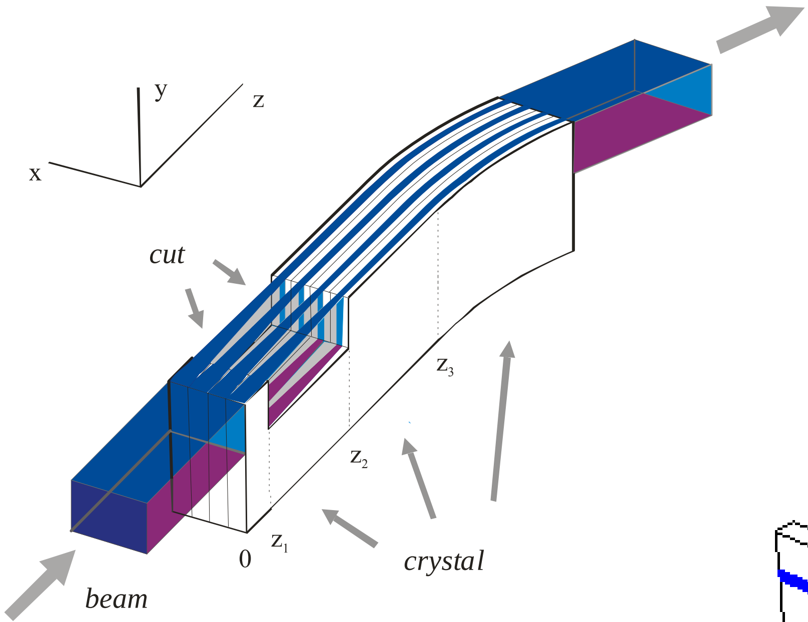
An idea for future development

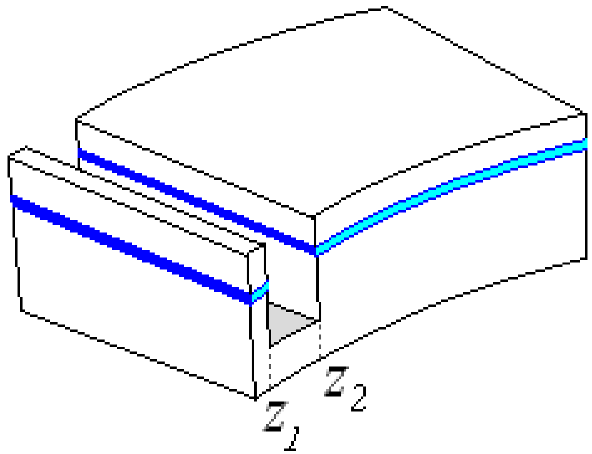


The capture probability

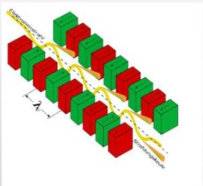
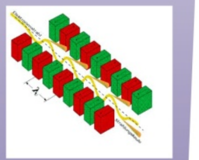
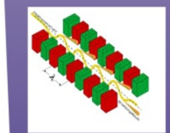
increase by crystal cut

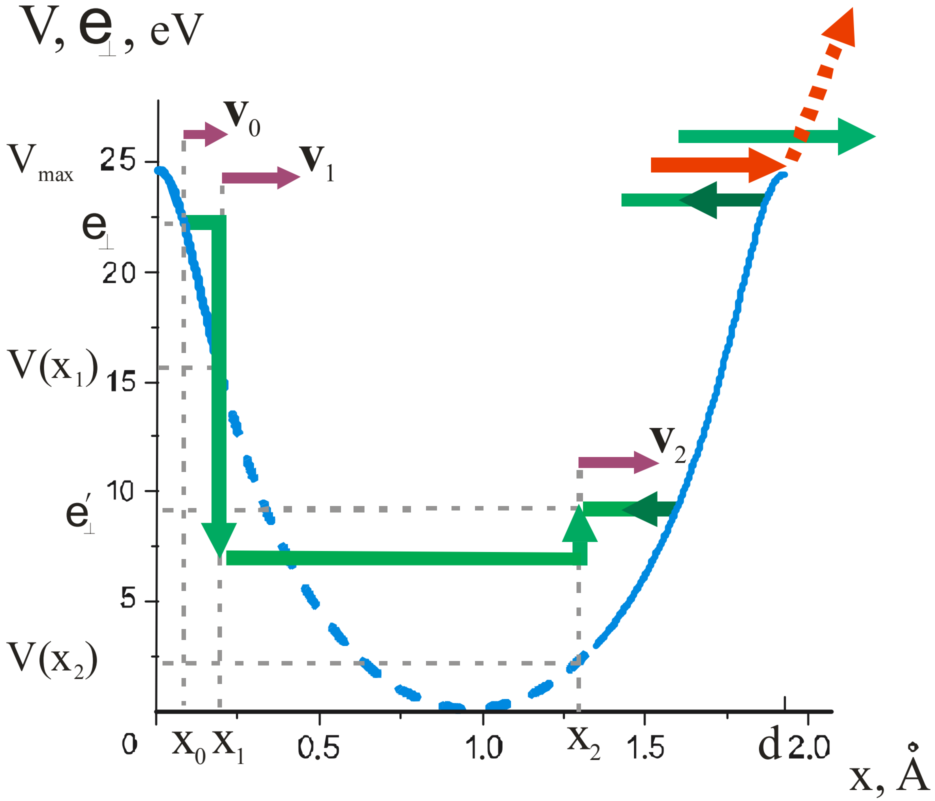
V.V.*Tikhomirov, JINST, 2(2007)P08006*





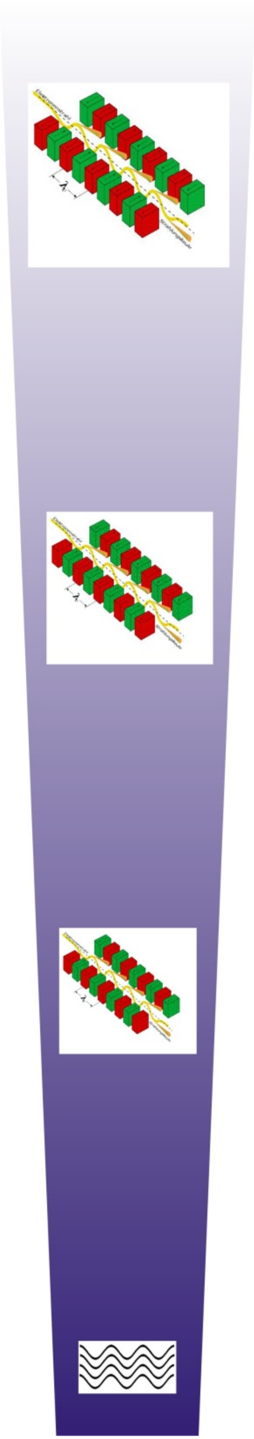
Transverse energy reduction *by the cut - 1*

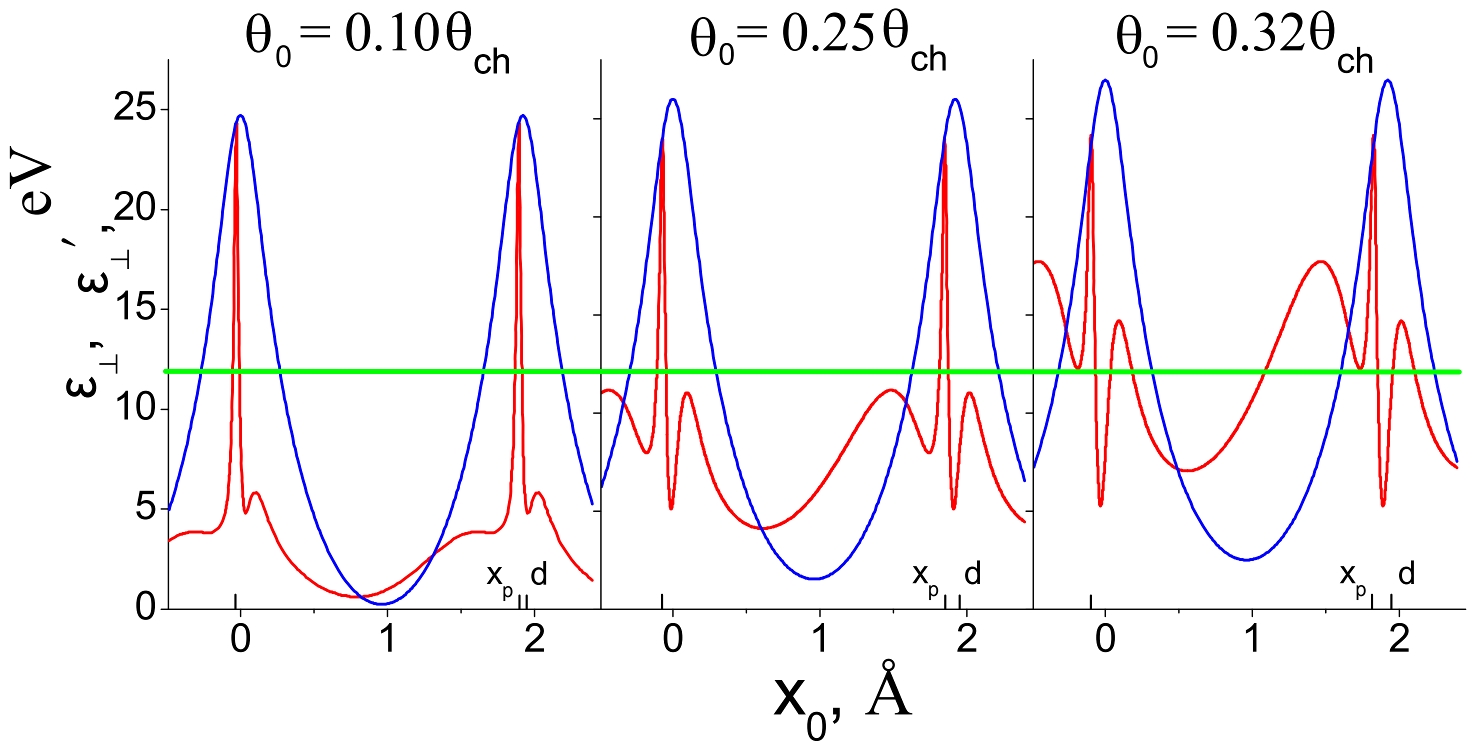






The cut diminishes the potential energy conserving the transverse kinetic one

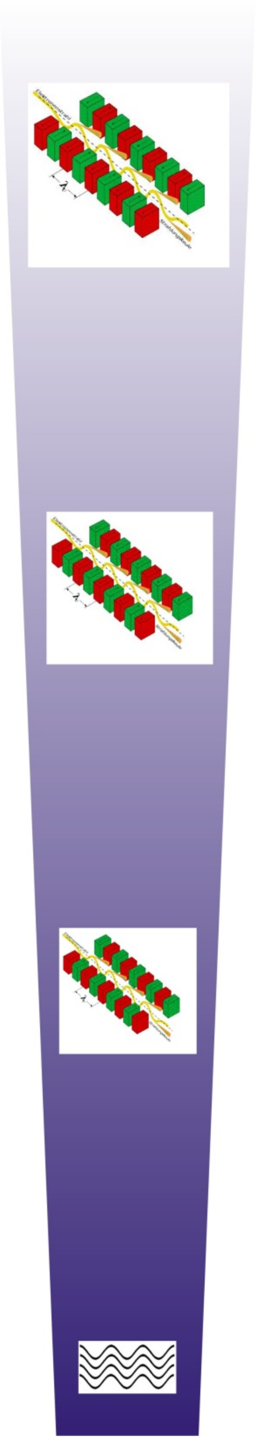
Transverse energy reduction ***by the cut - 2***

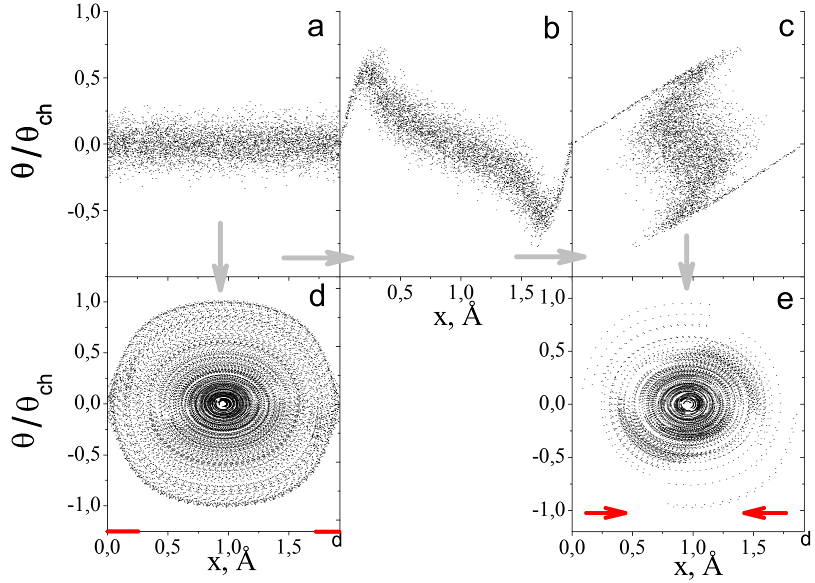


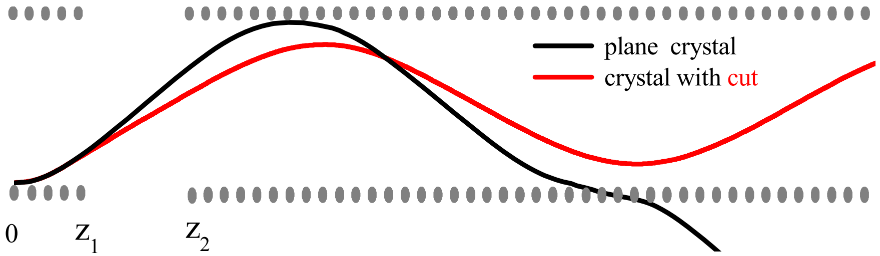


Only 1-2% of protons avoid drastic transverse energy reduction by the cut

Phase space transformation by the cut

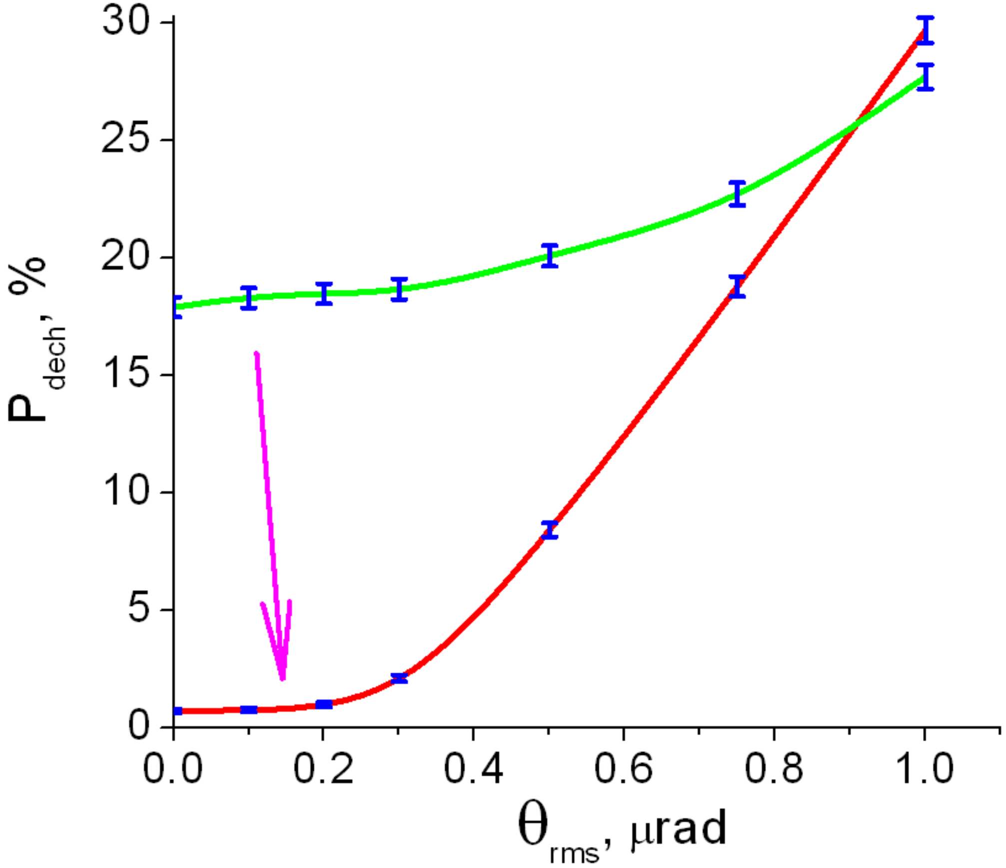






Protons cease to reach the high nuclear density regions

Channeling fraction increase by the cut



The cut increases channeling fraction from 85 to 99%

Cut formation method

(110) Silicon Etching for High Aspect Ratio Comb Structures

*Seong-Hyok Kim, Sang-Hun Lee, Hyung-Taek Lim, and Yong-Kweon Kim
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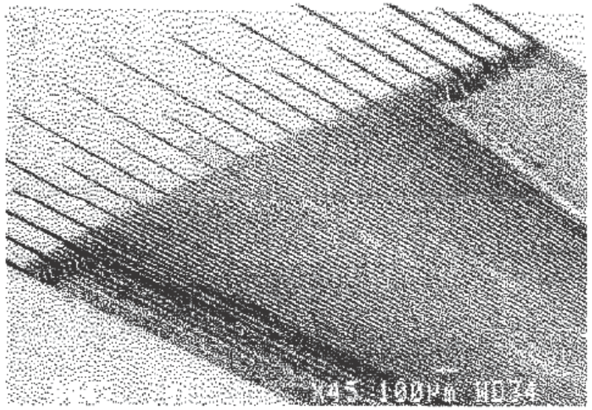


Fig 1. SEM photograph of alignment target after wet etching

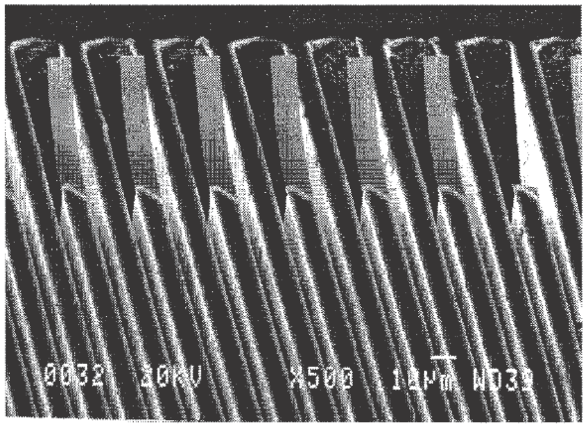
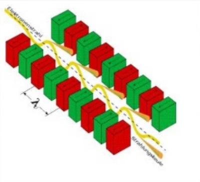
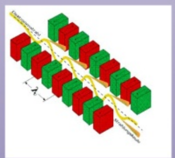
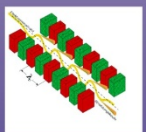


Fig. 12 Fabricated comb structures.
The width is 8μm, gap is 7μm and height is about 150μm

Crystal cut can be produced by
anisotropic etching







Japanese Journal of Applied Physics
Vol. 45, No. 4A, 2006, pp. 2395–2407

Invited Review Paper

Ultimate Top-down Etching Processes for Future Nanoscale Devices: Advanced Neutral-Beam Etching

Seiji SAMUKAWA*

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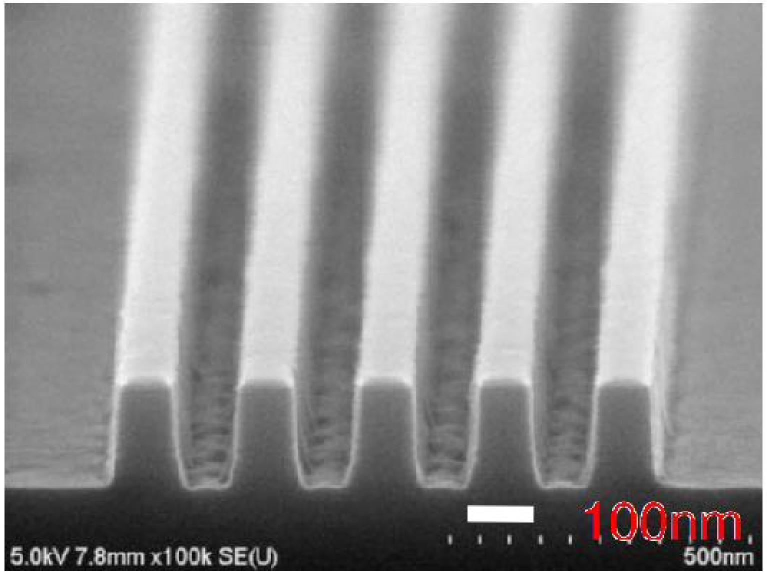
(Received August 4, 2005; accepted November 15, 2005; published online April 7, 2006)

For the past 30 years, plasma etching technology has led in the efforts to shrink the pattern size of ultralarge-scale integrated (ULSI) devices. However, inherent problems in the plasma processes, such as charge buildup and UV photon radiation, limit the etching performance for nanoscale devices. To overcome these problems and fabricate sub-10-nm devices in practice, neutral-beam etching has been proposed. In this paper, I introduce the ultimate etching processes using neutral-beam sources and discuss the fusion of top-down and bottom-up processing for future nanoscale devices. Neutral beams can perform atomically damage-free etching and surface modification of inorganic and organic materials. This technique is a promising candidate for the practical fabrication technology for future nano-devices. [DOI: 10.1143/JJAP.45.2395]

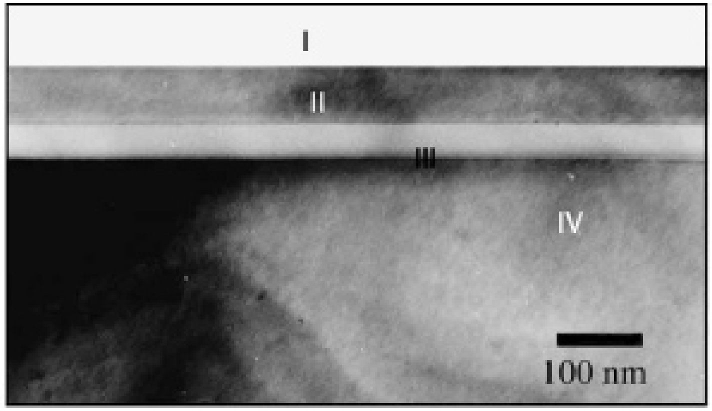
KEYWORDS: top-down process, plasma etching, radiation damage, neutral beam, sab-10 nm patterning

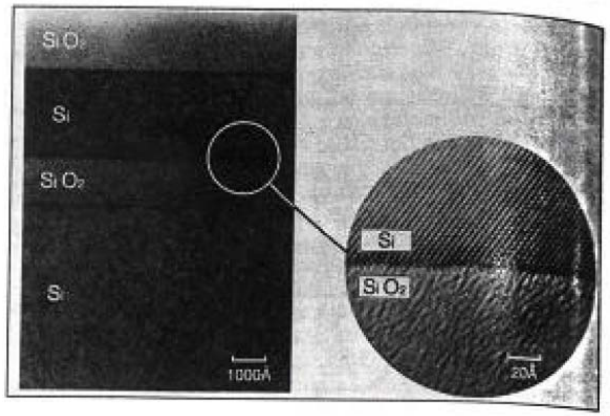


SIMOX Buried Oxide Layer can be used instead of crystal cut

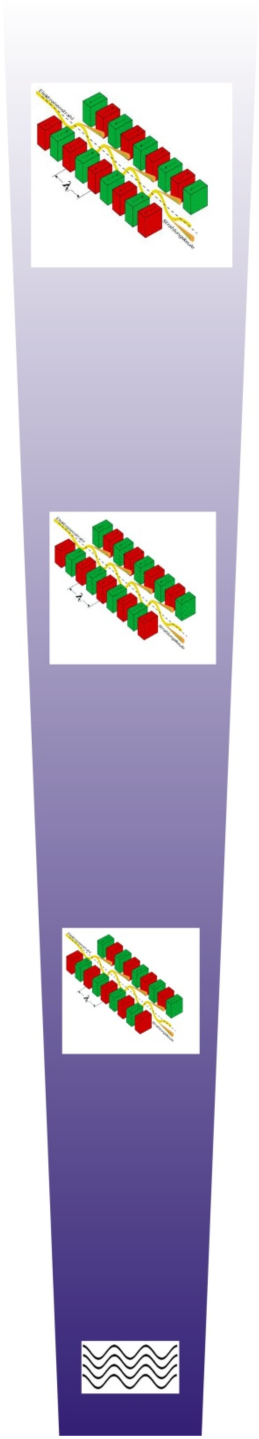
V. Guidi, A. Mazzolari and V.V. Tikhomirov,

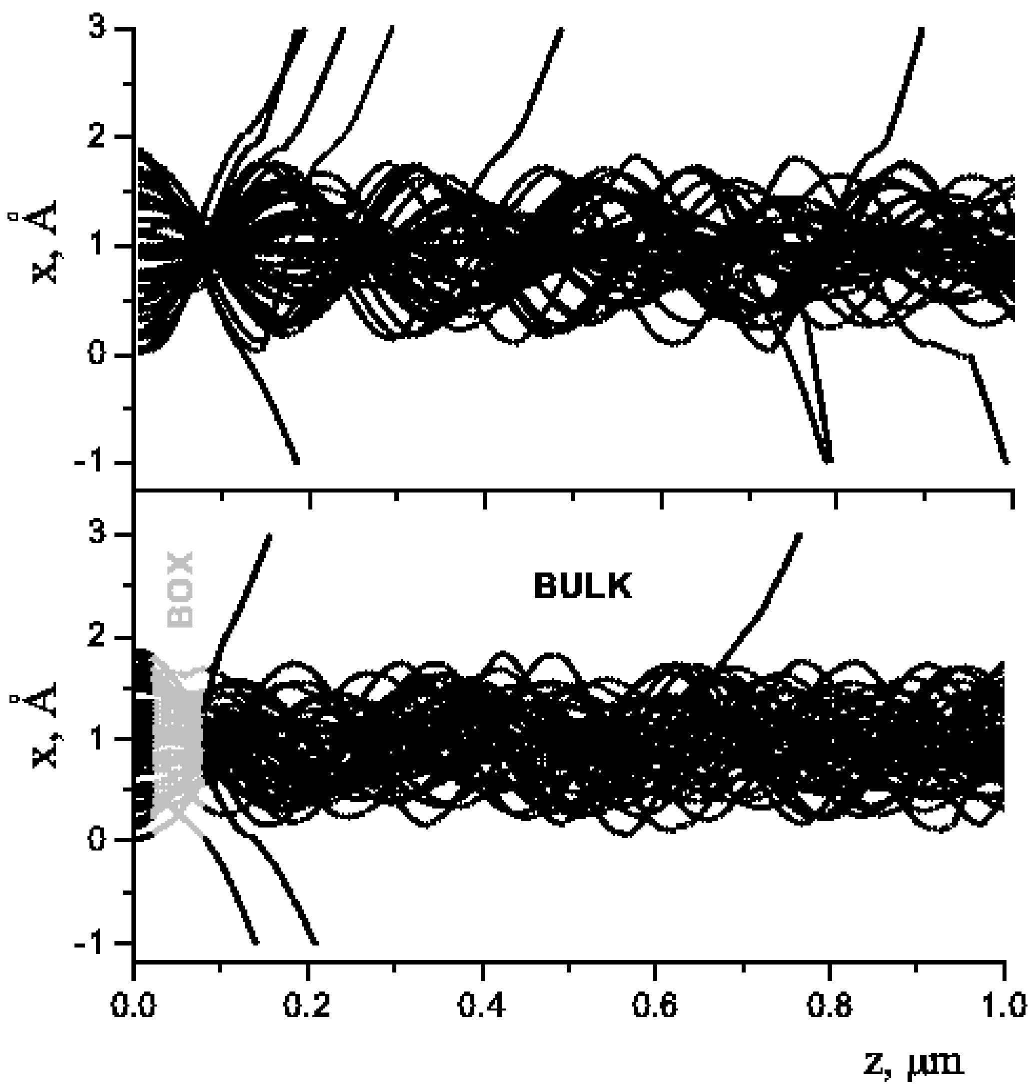
J. Phys. D: Appl. Phys. 42**(2009) 165301**





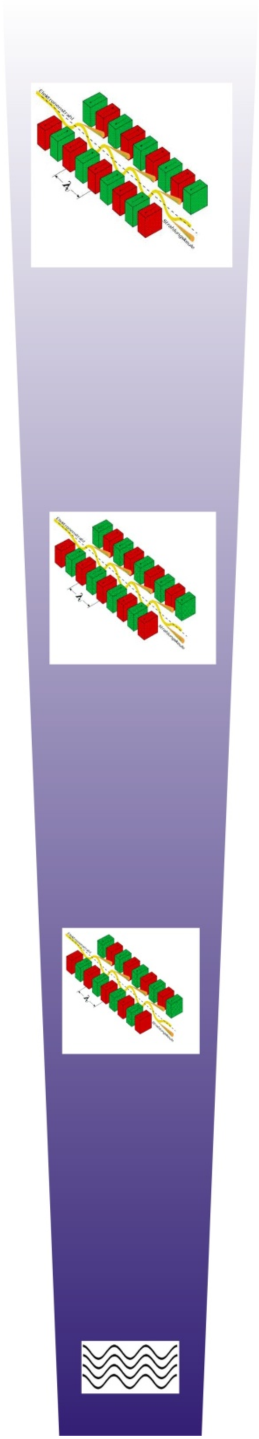
- Thermal annealing restores silicon cristalline quality and creates a buried SiO_2 layer,
- Interfaces between Si and SiO_2 are well terminated,
- Misalignment between silicon layers in available SIMOX structures: less than 0.7 Å/mm.



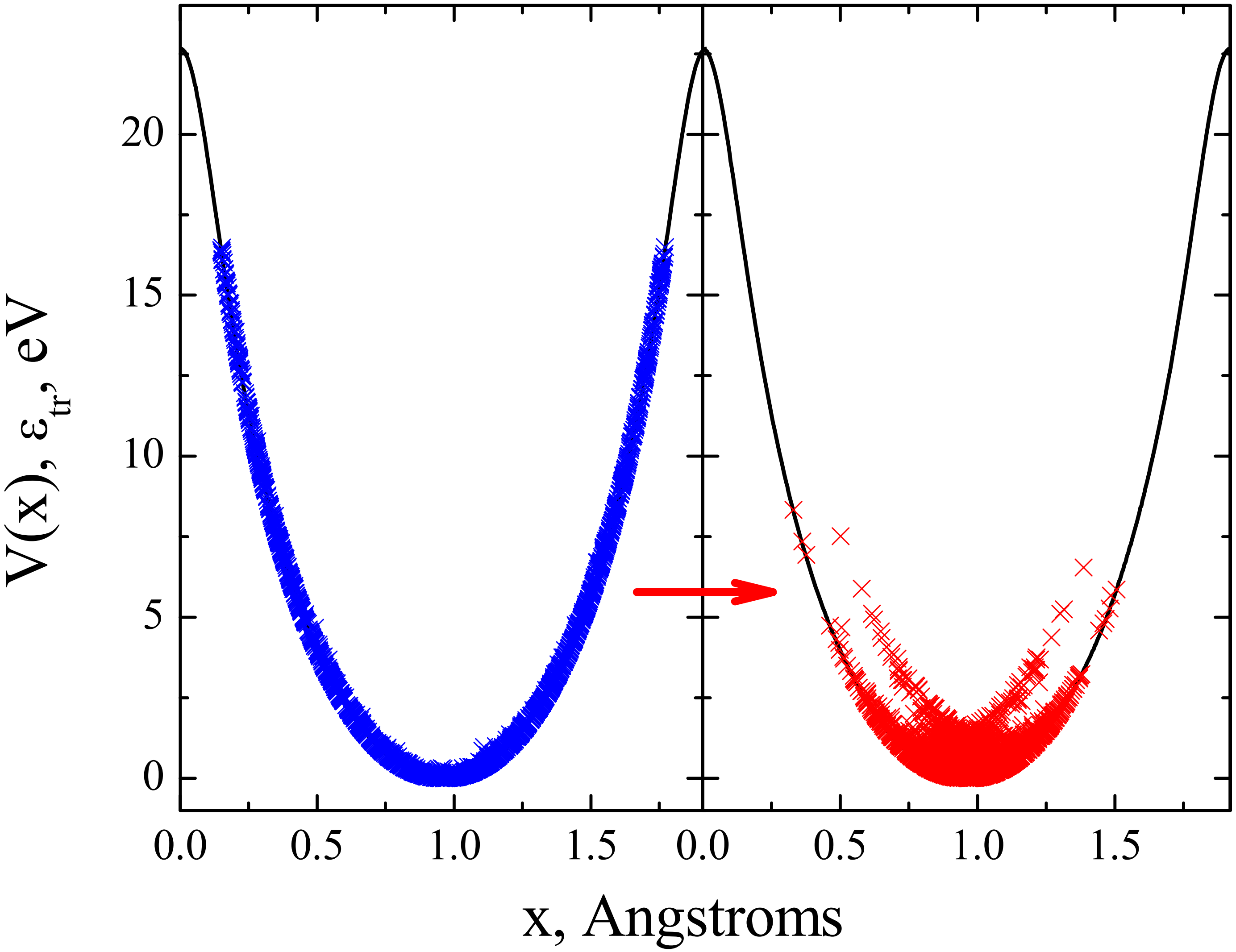


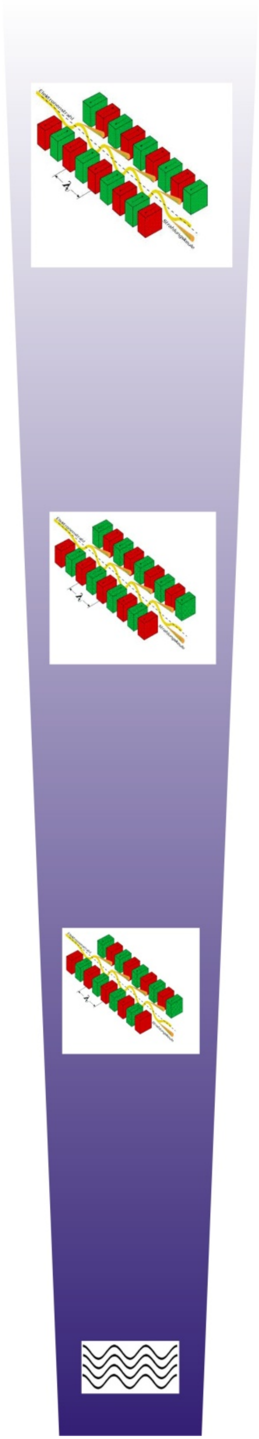
BOX layer "focuses" protons like a ***cut*** diminishing their transverse energy

$$z_1 = 20\, nm,$$
$$z_2 = 80\, nm,$$
$$z_3 = 1\ \mu m,$$
$$E_p = 7\, MeV$$

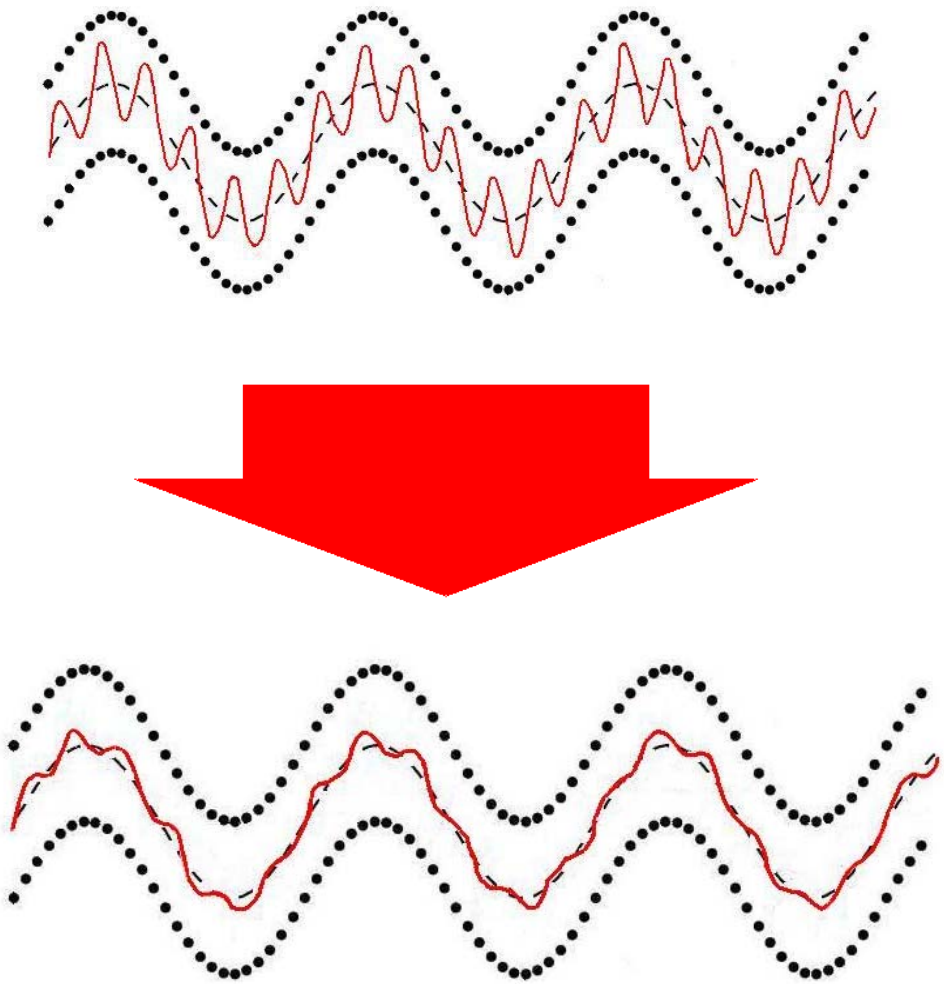


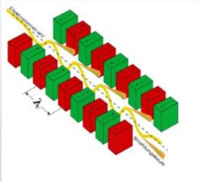
transverse energy reduction by **cut**

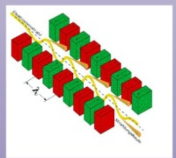


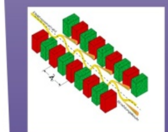


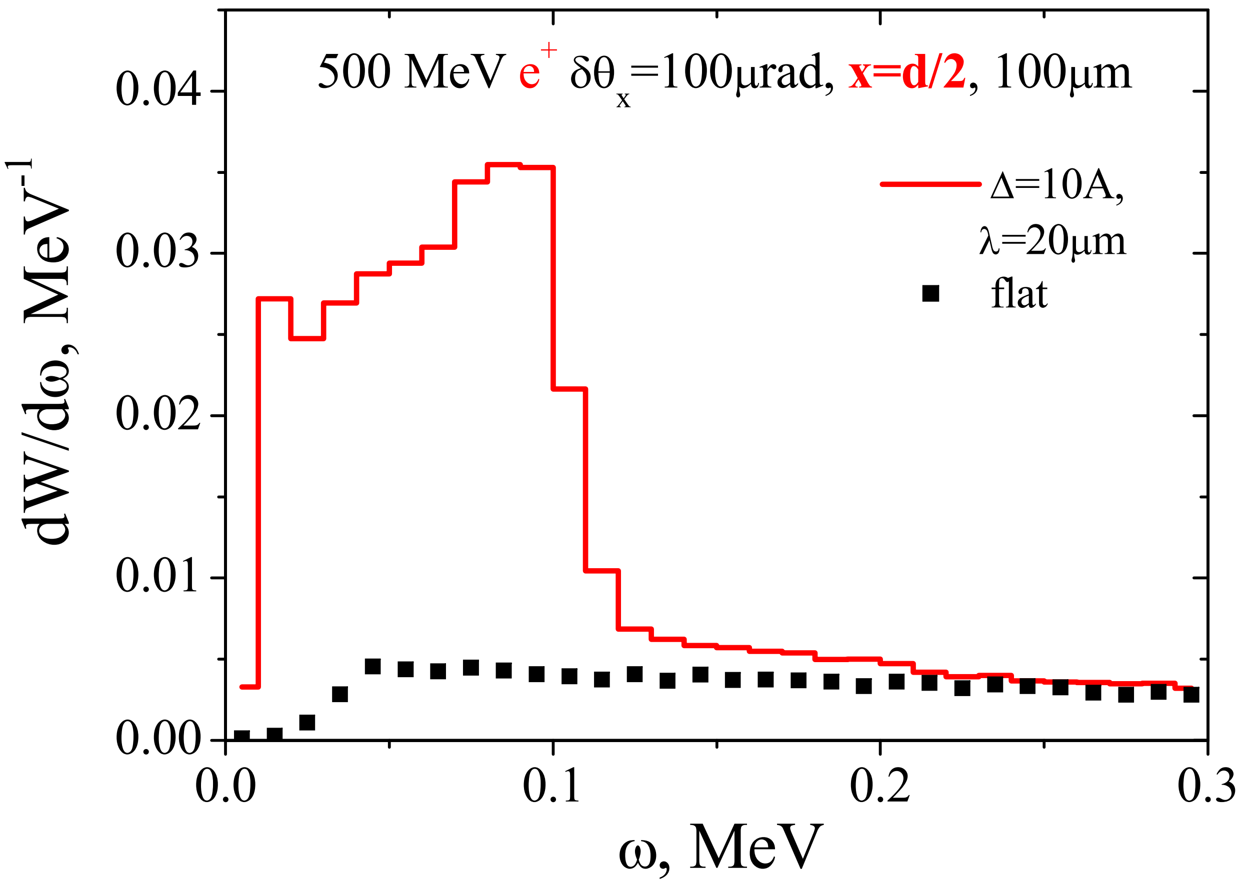
The **cut** allows to diminish channeling oscillations:

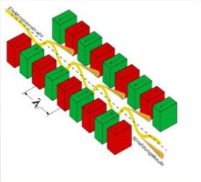


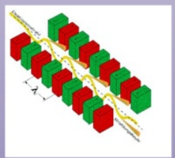


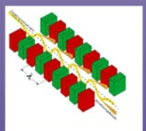





500 MeV e+ δθx=100μrad, x=d/2, 100μm
Δ=10A,
λ=20μm
flat
dW/dω, MeV-1
ω, MeV
0.00
0.01
0.02
0.03
0.04
0.0
0.1
0.2
0.3







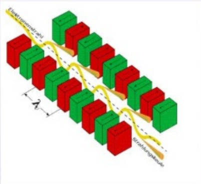
Essential CU improvement by diminishing of channeling oscillations by the crystal **cut**

- *increase of number of particles*
- *increase of radiation intensity*
- *decrease of undulator period*
- *narrowing of radiation spectrum*
- *elimination of energy losses for channeling radiation*

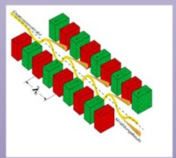
A real way to both

γ-laser and high positron energies

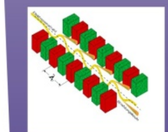
Conclusions



Electron *radiation in CU represents a good testbed for simulation methods*



Positron *radiation in CU can be observed under reasonable bam quality*



Crystal cut *can improve the CU functiomig in numerous directions*

Positron CU radiation + photon diffraction open up a way to **γ-laser**

Thank you for attention!