# Advanced Channeling for Novel Accelerator Concepts

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*…thanking all colleagues who contributed to this knowledge…*
*special ones for Dik Alexey and Frolov Eugeny*

# @ medium for acceleration…

In 1956 at CERN meeting Veksler for the first time proposed for a wide discussion:

COHERENT PRINCIPLE OF ACCELERATION OF CHARGED PARTICLES

*A: In all existing accelerators of charged particles, the constant and varying electric field accelerating them is created by a powerful external source, and hence the strength of the field is independent, in the first approximation, of the number of particles which are being accelerated.*

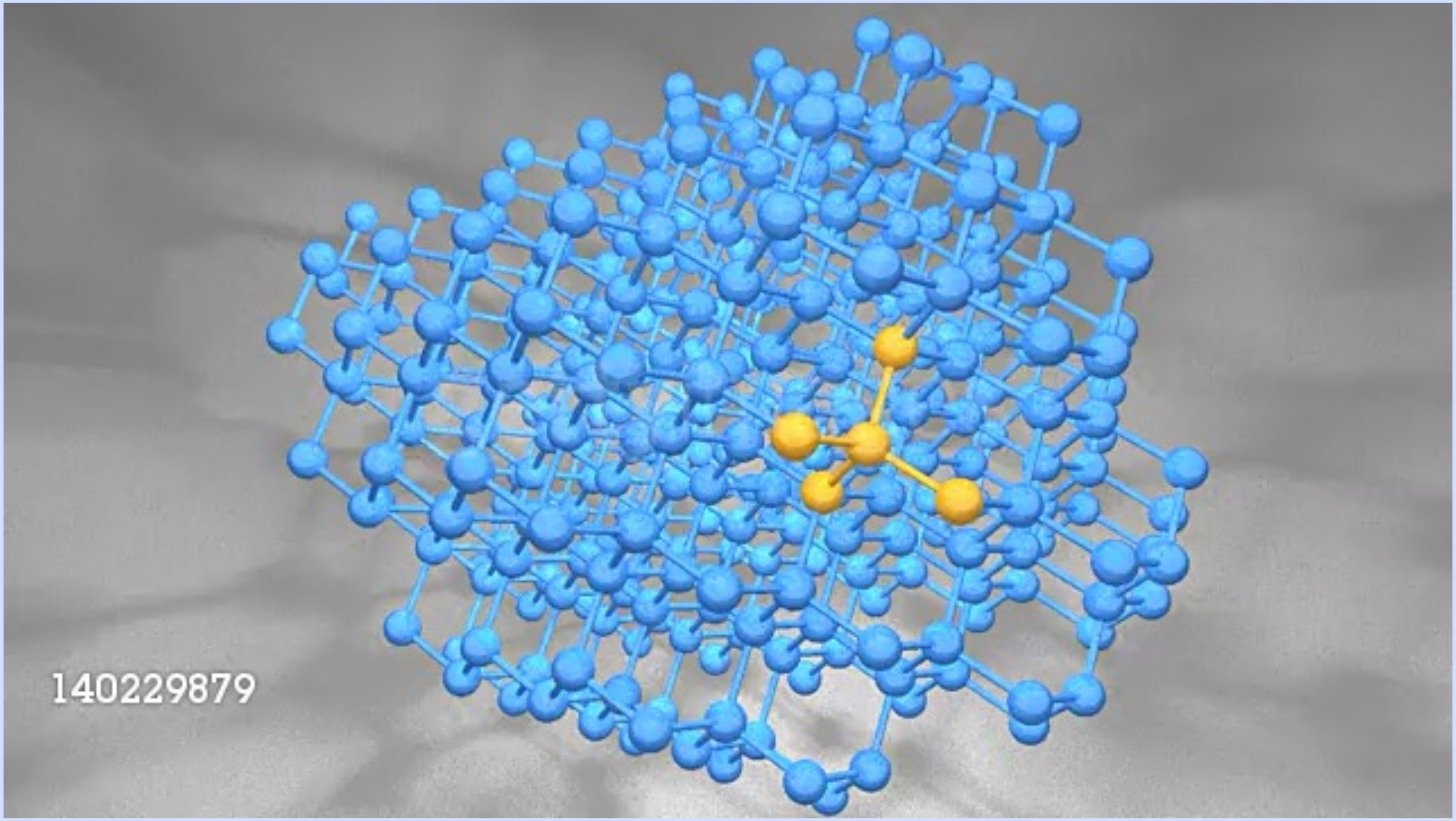
B: **... particle-accelerating electric meld is produced by the interaction of a geometrically small group of accelerated particles with another group of charges, plasma or an electromagnetic wave.**

Main pricnciples of new acceleration:

- the magnitude of the accelerating field produced by this interaction and acting on each particle depends on the number of accelerated particles;
- synchronization between the accelerating field and the motion of the accelerated bunch is automatically maintained;
- high field strengths can be created only at those points where the accelerated particles are located;
- neutral bunches of particles can be also accelerated.

# @ channeling…

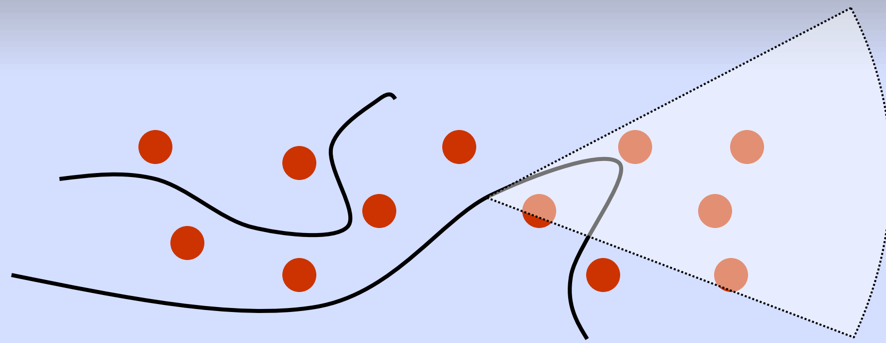
...well known since the beginning of semiconductor business, first simulated in the beginning of 1960-s, and formulated (phenomenology) in 1965...




*...orientation dependent density... not only for crystals (!)*

# @ channeling of charged particles in crystals

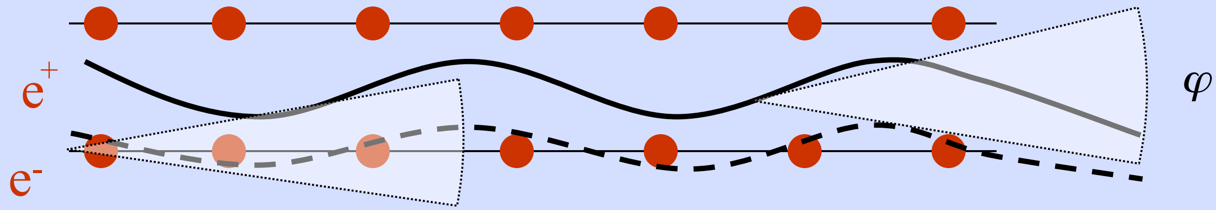
@ Amorphous:



@ Channeling: → **1** *...order...*

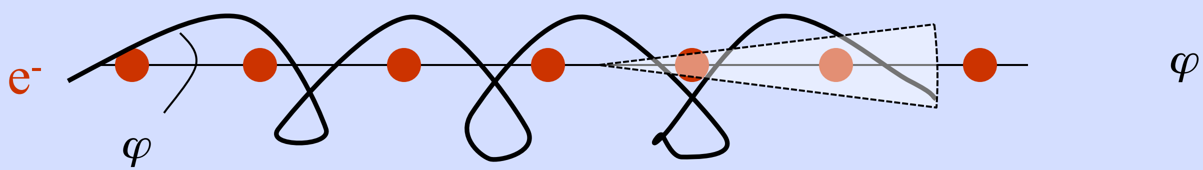
*Atomic crystal plane – averaged/smeared continuous potential*

planar




*Atomic crystal row (axis) - averaged/smeared continuous potential*

axial

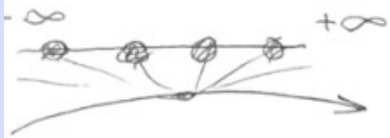



→ **2** *...small angle to main crystal directions...*

$\varphi << 1$ $\left(\varphi < \varphi_L \sim \sqrt{U/E}\right)$ - *the Lindhard angle is the critical angle for channeling*

# @ channeling continuum potential: some estimations for e- in a crystal

$V_a \propto \frac{Ze^2}{r}$ → screening → $V_{as} \propto \frac{Ze^2}{r}\,\underbrace{\varphi(r/a_s)}_{\text{screening function}}$




$V_{axis} \to \langle V_{as} \rangle$ over all atoms of the axis

$$\langle\ \rangle \propto \int_{-\infty}^{+\infty} \frac{Ze^2}{r}\varphi(r/a)\,dr$$

$Ze^2 \to Z \propto 1 \div 10^2$

$e^2 \simeq 14.4\ \text{eV} \cdot \text{Å}$ || $\int_{-\infty}^{+\infty} \frac{\varphi(r)}{r}\,dr$ || $|\varphi(r/a)| \to \{\text{total}, \text{no}\}$ ↓ $\{0 \div 1\}$

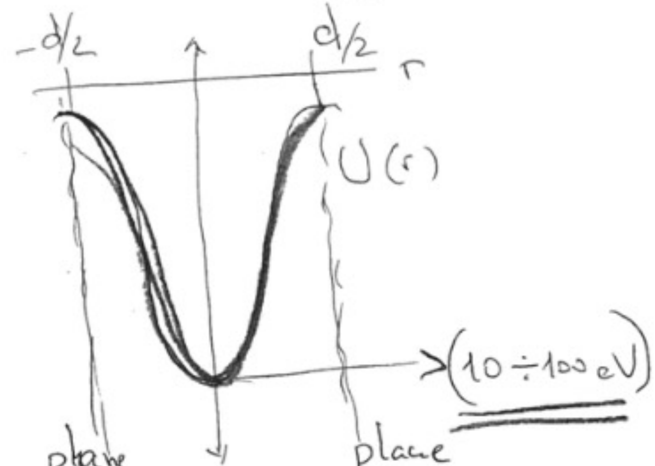
⇓

$V_{axis} \to \langle V_{as} \rangle_{atoms}$

$V_{plane} \to \langle V_{as} \rangle_{plane\ atoms}$

$$\boxed{|U_{cr}(r)| \to \{10 \div 10^2\}\ \text{eV}} \Rightarrow$$

crystal continuous potential



# @ crystal fields for beams shaping/acceleration

$\left|\partial U/\partial x\right|$ → gradient defines the ability to handle the beam by $U(x)$

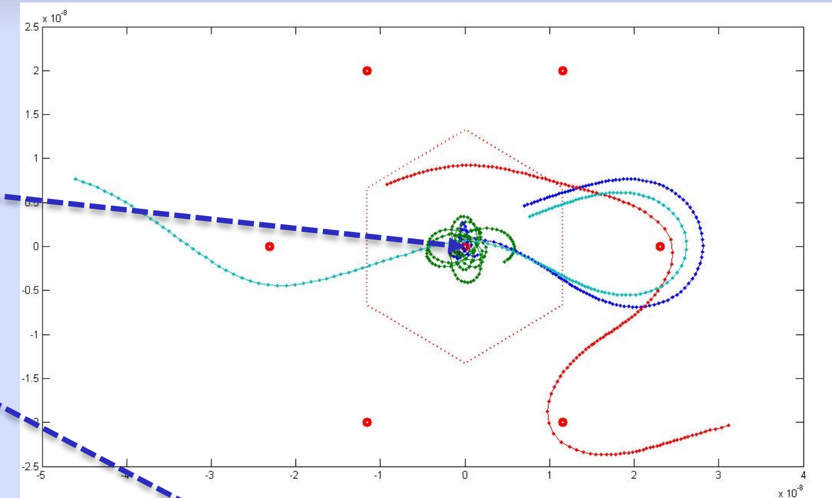
$\left|\partial U/\partial x\right|_{\text{modern accelerators}} \propto (10 \div 10^2\ MeV/m)$ → (!)

$\left|\partial U/\partial x\right|_{\text{crystal}} \propto 1 \div 10^2\ eV/Å \Rightarrow (10 \div 10^3\ GeV/m)$

Crystal fields can provide much bigger gradients than modern accelerator fields

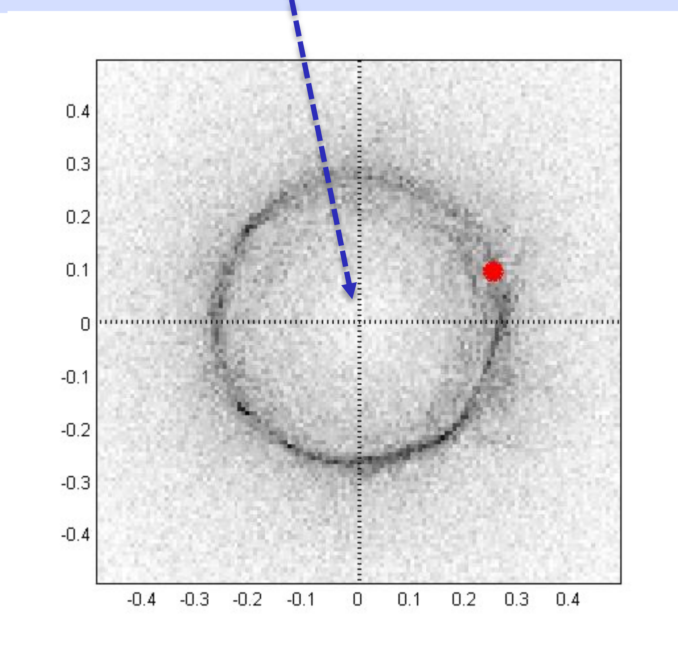
# @ electron beam dynamics in crystals: simulations

*Ge <111> e- 150 MeV*




*various trajectories transverse axis cross-section*

*Computer simulations for angular distribution of a beam vs depth of penetration*

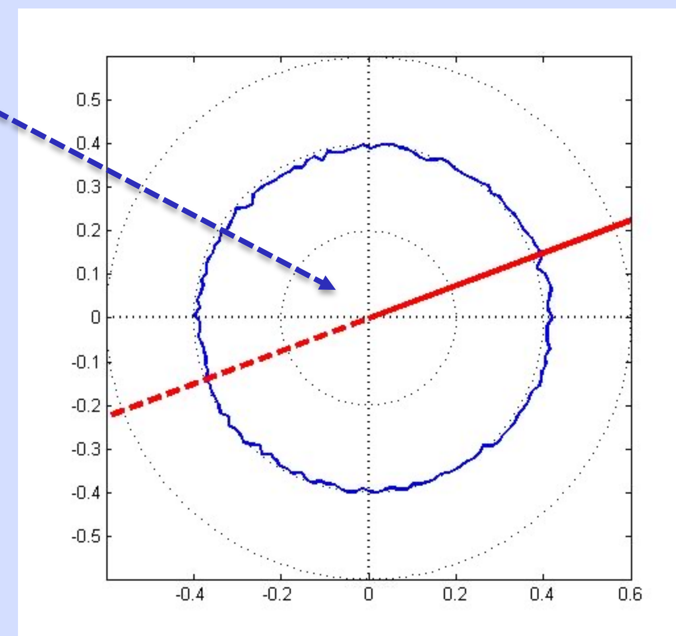



*$\Delta\theta = 0$ – beam divergence*

*$\theta_0 = 0.25\ \theta_c$ – incidence angle*

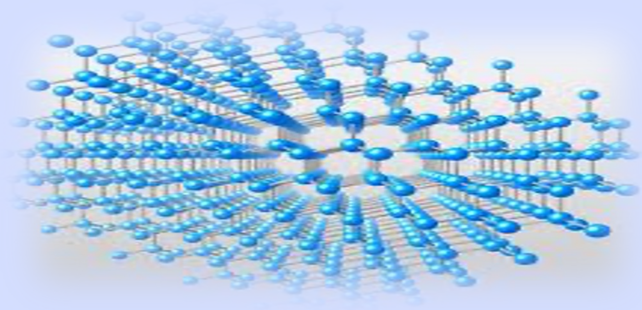
*depth evolution*

*$\Delta t$ = 81 nm ÷ 1.33 μm*

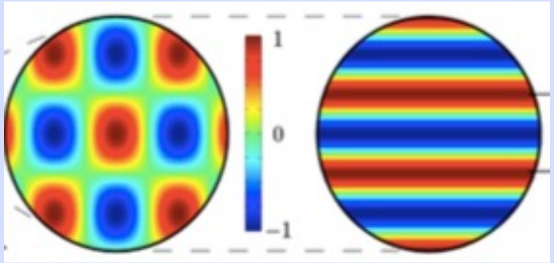


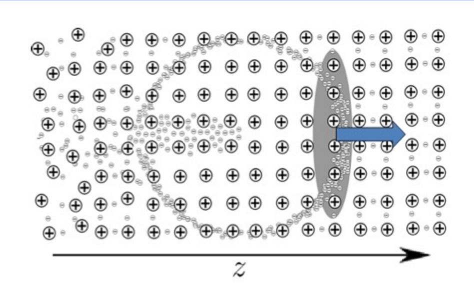
# Channeling based applications for Charged & Neutral Beams: from Crystal to Capillary guides

- **Crystal Channeling**
  - Beam shaping;
  - Micro-undulator;
  - Positron source

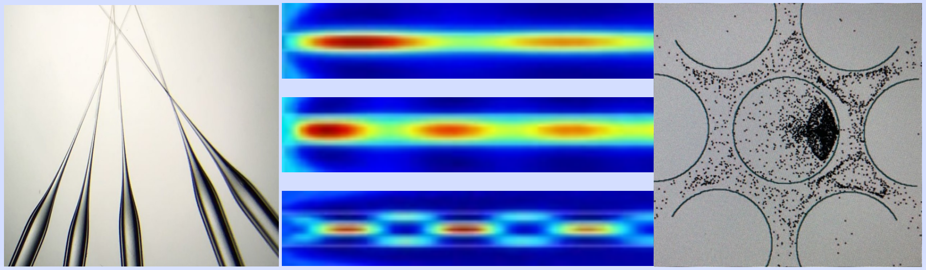


- **Laser & Plasma Channels**
  - Beam profiling for high current/luminosity;
  - Dynamics for wake field acceleration;



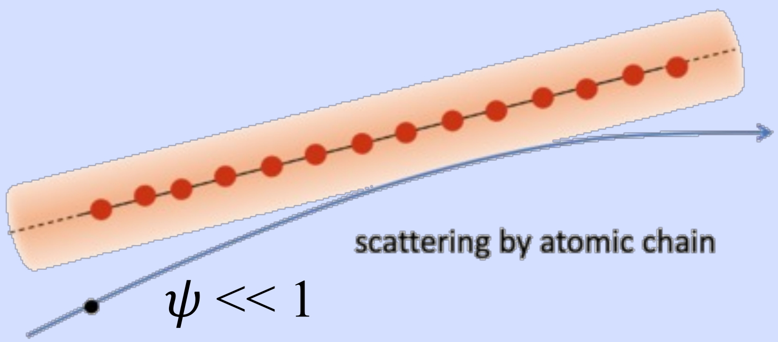



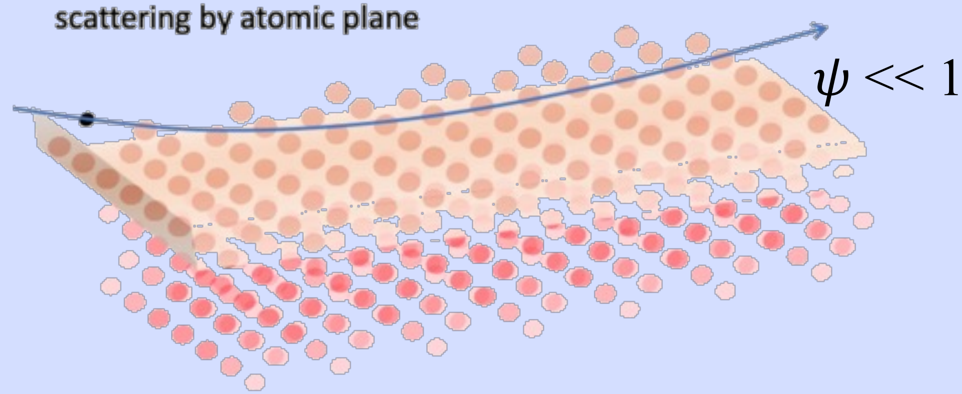

- **Capillary μ- and n-Channels**
  - beam redistribution;
  - Compact storage (?)



# @ surface potential for reflection: first attempts - basics

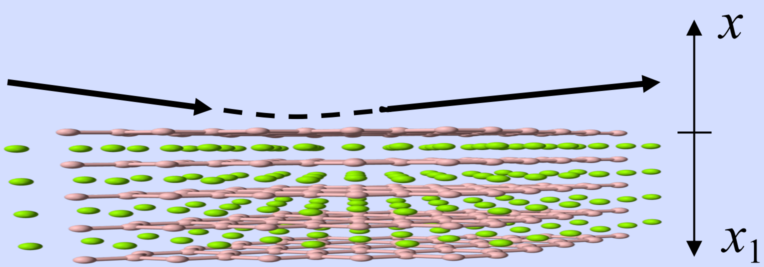
In the mid 80th of the last century Kumakhov & colleagues proposed to use smooth surfaces for effective deflection of charged particles... and further slowly bent surfaces for larger beam deflection




In case of amorphous, the interaction potential, i.e. surface potential, is the potential for one atom integrated by all volume atoms

Interaction potential with a surface at grazing incidence as continuous surface potential

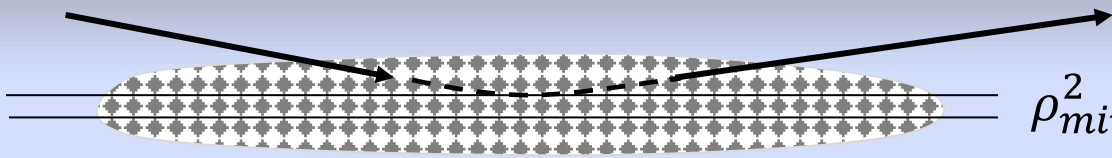



$$\mathbf{V}_{am}(x) = N_a \int_x^{\infty} V_a(x_1)\,dx_1$$

*many-sliced planar potential*

$$\mathbf{V}_{am}(x) = 2\pi N_a Z_p Z_a e^2 a_{TF}^2 \sum_{i=1}^{3} (\alpha_i/\beta_i^2)\exp(-\beta_i x/a_{TF})$$

# @ surface channeling: multiple mirror reflection for bending

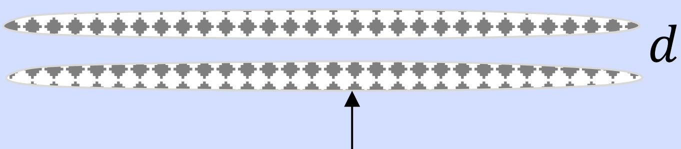


$\rho^2_{min} \approx (\rho^2 \ + a^2)$ mirror reflection

Amorphous surface potential
//Molier approximation//

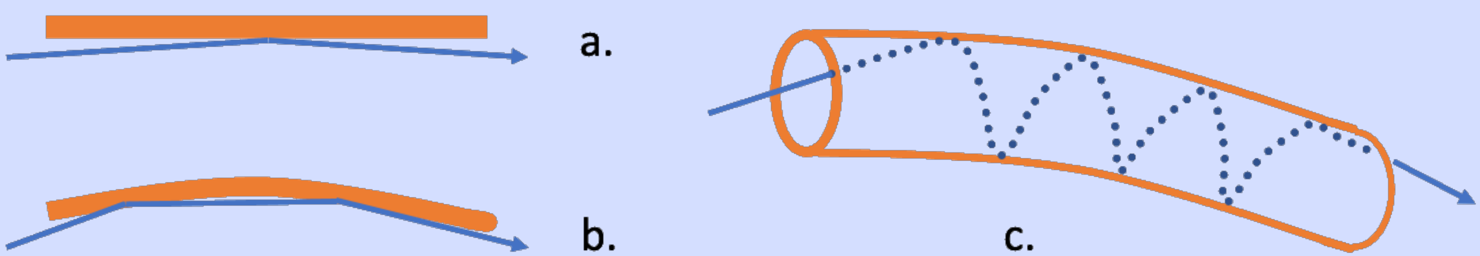
$$\mathbf{V}_{am}(x) = 2\pi N_a Z_p Z_a e^2 a_{TF}^2 \sum_{i=1}^{3} (\alpha_i/\beta_i^2)\exp(-\beta_i x/a_{TF})$$

$\psi_c^2 \approx V_a \ (\rho_{min})/\mathrm{E}$ - small critical angle of reflection ($\sim 10^{-5} \div 10^{-4}$)




channeling between 2 planes over a long distance

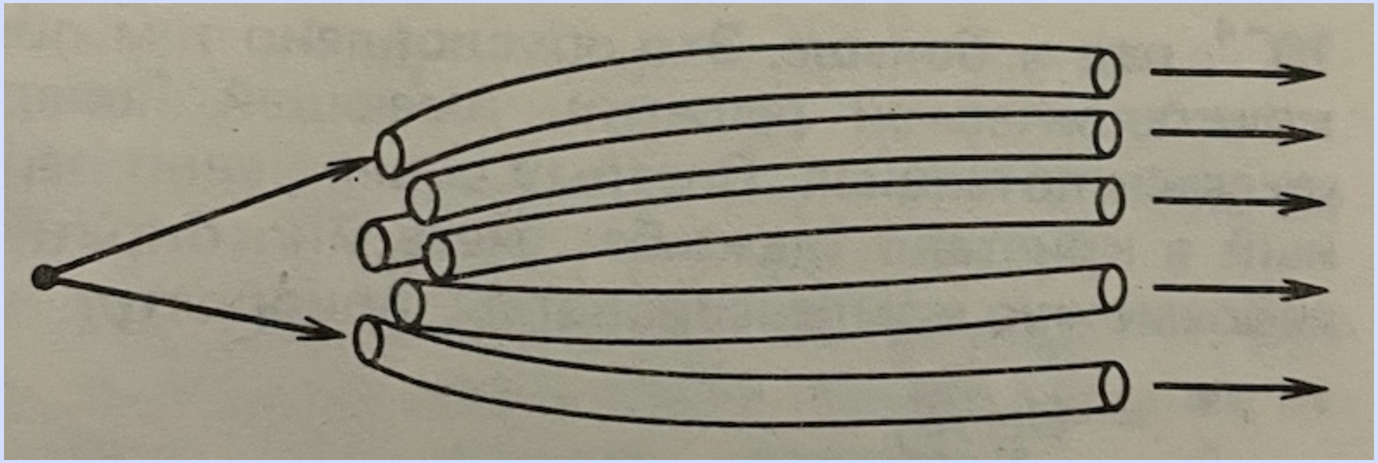
$R\psi_c^2 \approx d$ - effective bending by large angles




**a:** mirror reflection
**b:** multiple reflection 1d-bending

**c:** effective large angle 2d-bending

# Capillary Optics*…capillaries as guides for beams…*



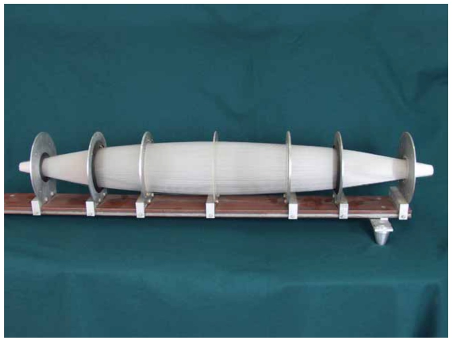
***Capillary based Ion Optics***

*proposed before 1985 in Lab for Electromagnetic Interactions KIAE!*

*Capillary guides reveals much advanced technological development leaving frozen capillary based ion optics practically for 10-15 years*

# Polycapillary optics *…evolution of the technology…*

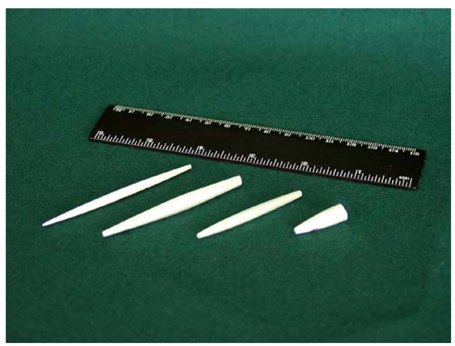
**1st - assembled lens made of single capillaries**



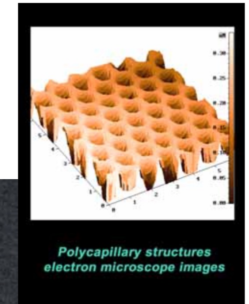
**2nd - monolithic lens made of single capillaries**

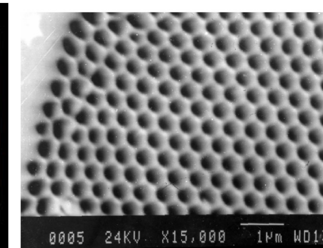
**3rd - assembled lens made of Poly capillaries**

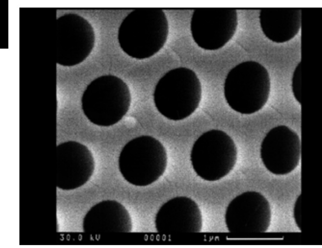
**4th - monolithic lens made of Poly capillaries**



**5th - monolithic integral micro lens**

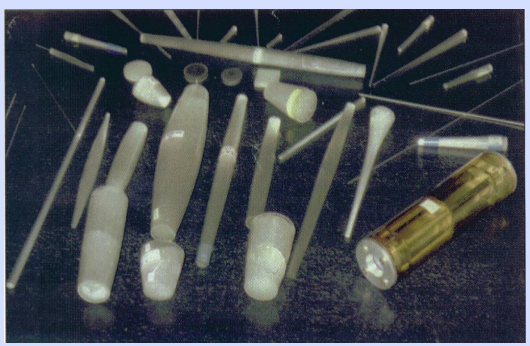



**Sub-Micron Capillary Technology**

## Technology: Drawing machines

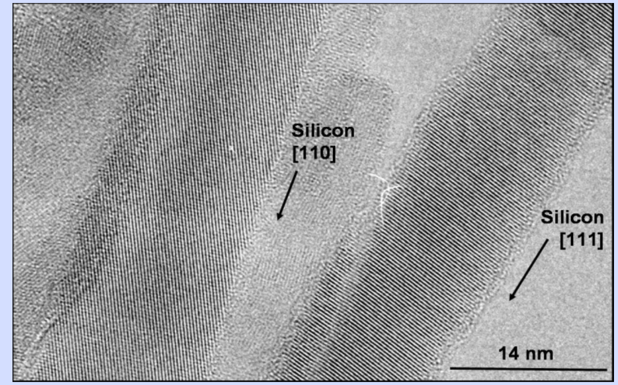
# Polycapillary optics *…from micro- down to nano-channels…*

Micro-
capillaries

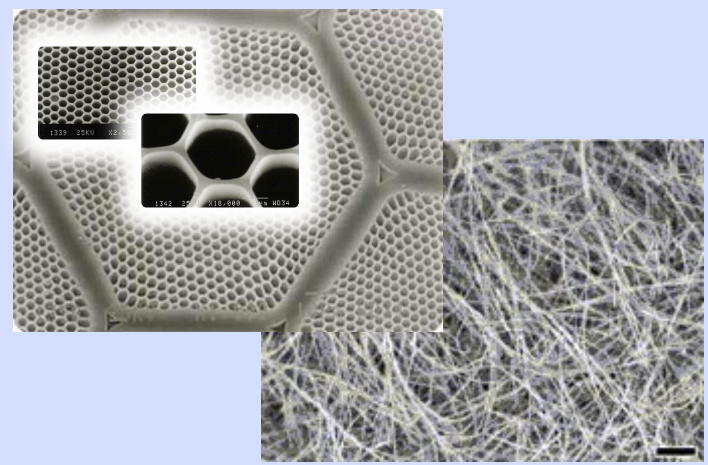


Micro → X-rays

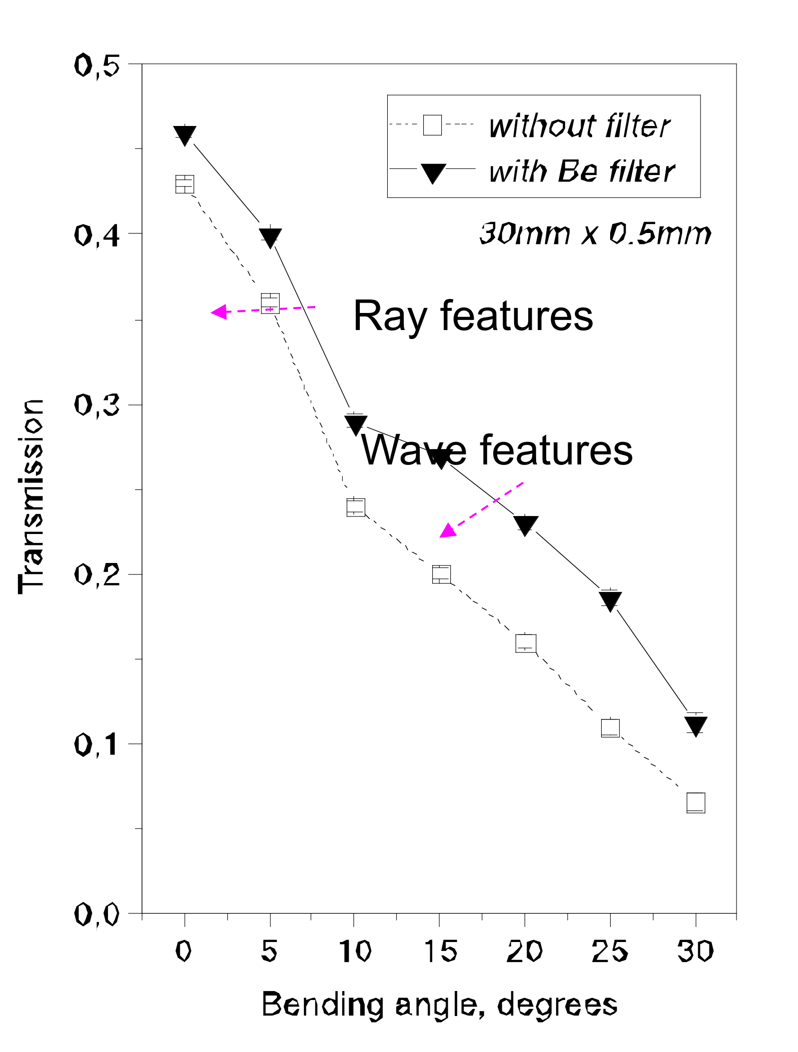
Nano → γ-rays (?)




Nanotubes &
Nanochannels

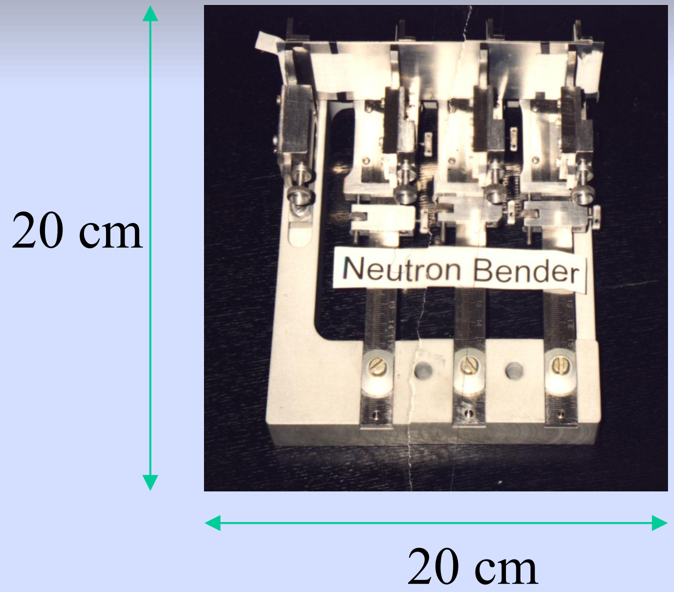


# @ neutron beam bending




*Transmission of thermal neutrons by a system of bent polycapillaries as function of the bending angle.*

*<d> ~ 10 μm <L> ~ 16 cm.*



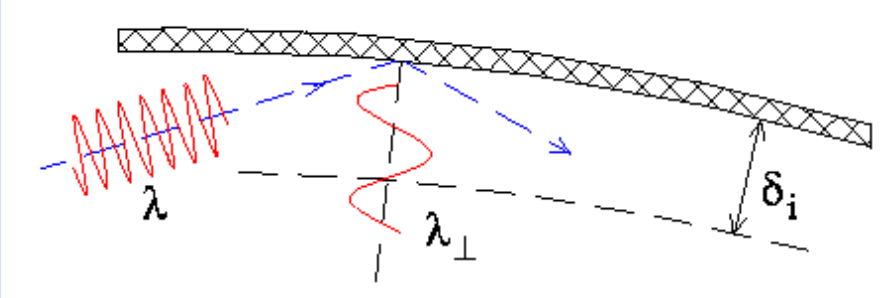

First capillary (poly) based thermal neutron bender applied at Hann-Meitner Inst (Berlin) in 1995.

# @ formation of surface modes

$$\vec{\mathbf{k}} = (\mathbf{k}_\perp, \mathbf{k}_{||})$$

$$k_\perp \simeq k\theta \ (\theta < \theta_c)$$

$$\lambda_\perp = \lambda/\theta >> \lambda$$




*Effective guide channel*

$$\delta_i(\theta) \simeq \lambda_\perp(\theta)$$

$$(r_{curv})_i = 1\,cm \div 1\,m$$

$$\theta \simeq 10^{-3} rad$$

$$\lambda \simeq 0.1 \div 10 \text{ Å}$$

$$(r_{curv})_i \theta^3$$

*Upper limit of the curvature radius*

$$(r_{curv})_m \sim 10 \ cm$$

$$\lambda \sim 1 \text{ Å}$$

# @ quantum basics for x ray channeling


$$\theta << 1$$

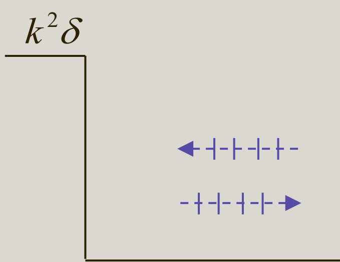
$$k_\perp \approx k\theta$$

$1^{st}$ *order:* $\Delta\varepsilon(\vec{r}) = 0$ *- no roughness*

*Wave equation:*

$$\Big(-\nabla^2 + \underbrace{k^2\delta(\vec{r}_\perp) - k_\perp^2}_{V_{eff}}\Big)E(\vec{r}_\perp) = 0$$

*plane surface*



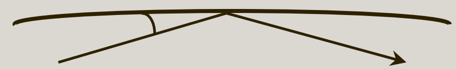

$$k^2\left(\delta(\vec{r}_\perp) - \theta^2\right) =$$

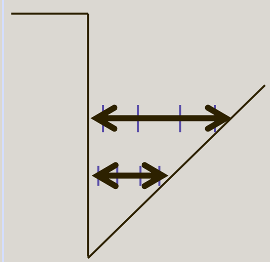
$$= \begin{cases} -k^2\theta^2, & r_\perp < r_1 \\ k^2\left(\delta_0 - \theta^2\right), & r_\perp \geq r_1 \end{cases}$$

$$\boxed{V_{eff} \equiv 0 \Rightarrow \theta_c \equiv \theta \approx \sqrt{\delta_0}}$$

TER

*curved surface*





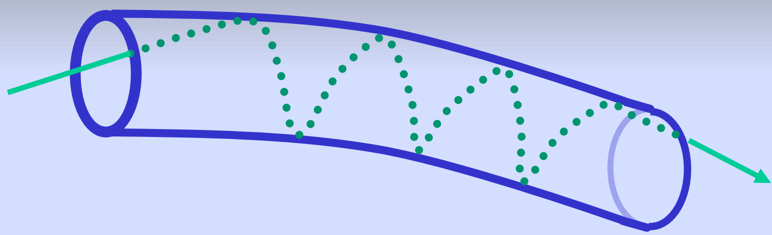
$$2\frac{-k^2 r_\perp}{r_{curv}}$$

*potential energy due to angular momentum* $\quad k r_{curv}\varphi$

$$\boxed{V_{eff} = k^2\left(\delta(\vec{r}_\perp) - \theta^2 - 2\frac{r_\perp}{r_{curv}}\right)}$$

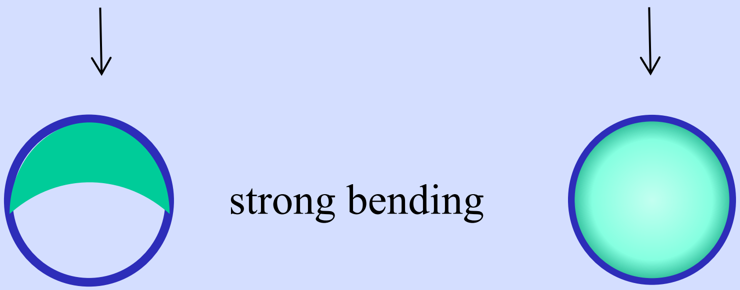
CHANNELING

# @ circular $\mu$-guide



$$E_n(r) \simeq \sum_m C_m u_m(\rho)\, e^{i\left(k_\parallel z + n\varphi\right)} \;,$$

$$u_m(\rho) \propto \begin{cases} Ai_m(\rho) \;, & \rho > 0 \text{ - guiding channel} \\ \alpha A{i'}_m(0)\, e^{\alpha\rho} \;, & \rho < 0 \quad (\alpha > 0) \text{ - cladding} \end{cases}$$




From well defined space-restricted radiation distribution at the entrance end to smeared over all cross-section distribution of a quasi polar symmetry with maximum *near* (*not at!*) the reflecting inner wall surface. The distribution is composed by many "photon trajectories" characterised by numerous variations of the curvature radius $r_1 \in (r_0, R)$.

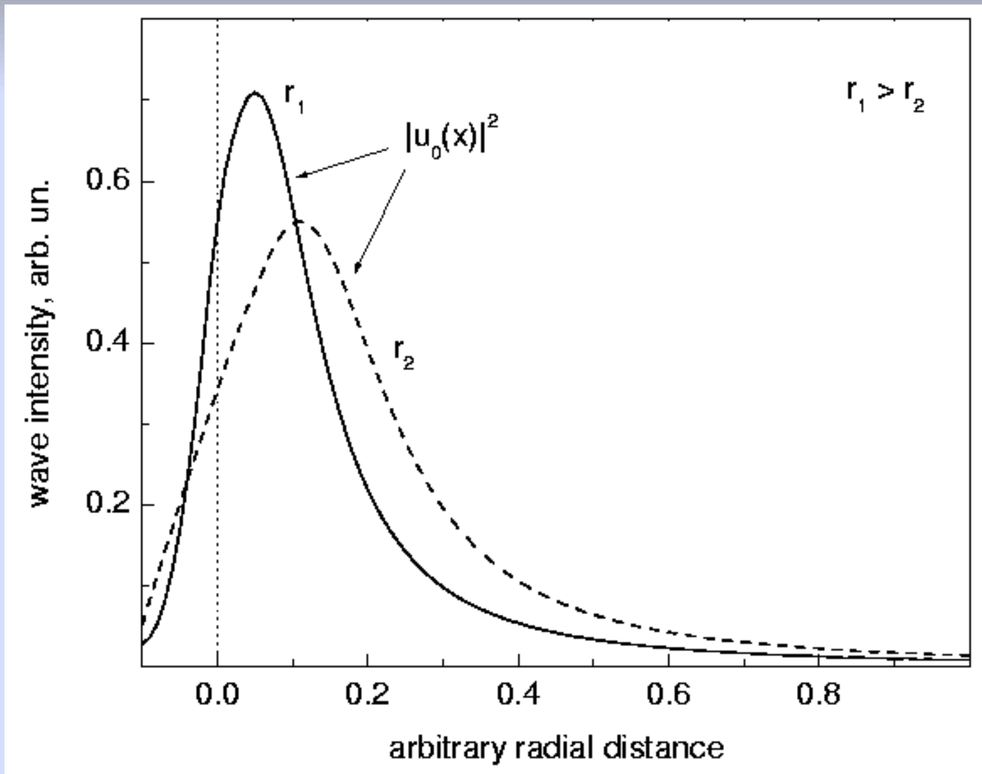
$$2\pi^2 \overline{u}_0^3 \simeq \lambda^2 r_1 \quad \longleftarrow \quad \text{single mode propagation}$$

curvature radius $r_1$ in the trajectory plane exceeds the inner channel radius, $r_0$ :

**$u_0 \gg \lambda$**

(for example, $u_0 \gtrsim 0.1$ µm for a capillary channel with the radius $r_0$=10 µm)

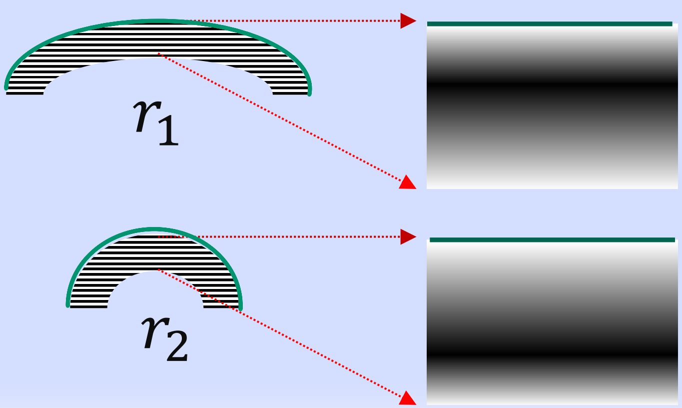
# @ smooth channel surface: radial wave distributions




*Decreasing in diameter results in spatial displacement of the distribution away the channel wall towards the center*

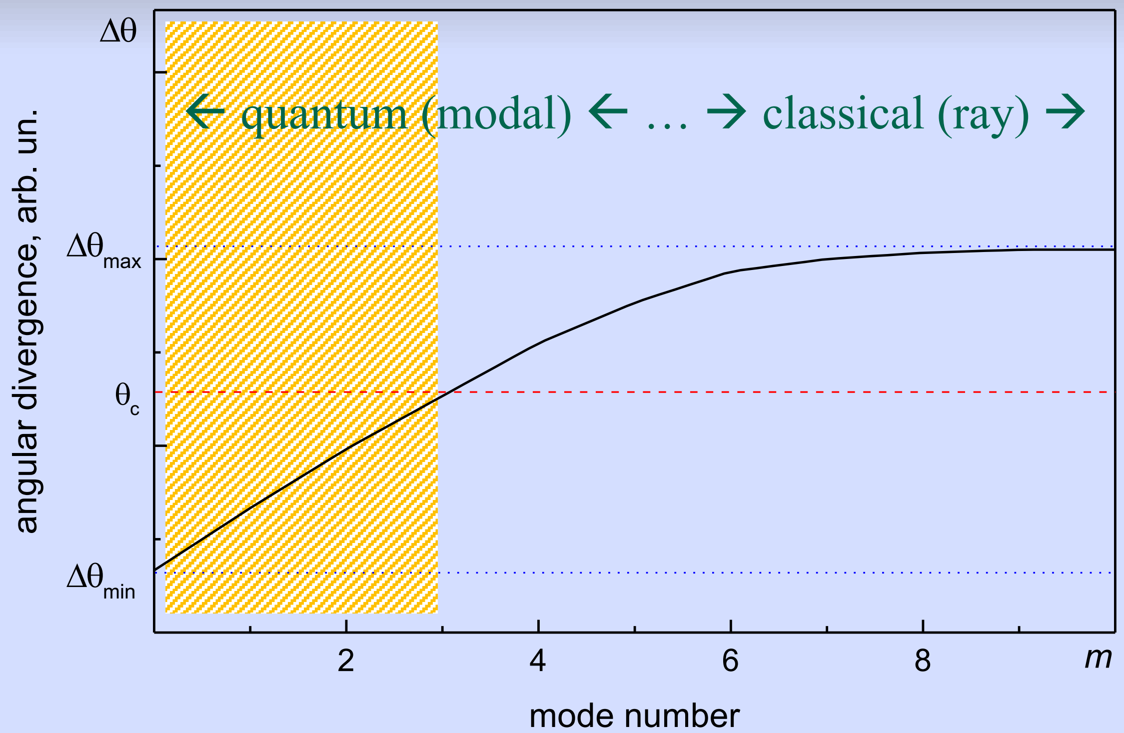
$$< u_0 > \simeq \left(\frac{\lambda^2 r_1}{2\pi^2}\right)^{1/3}$$

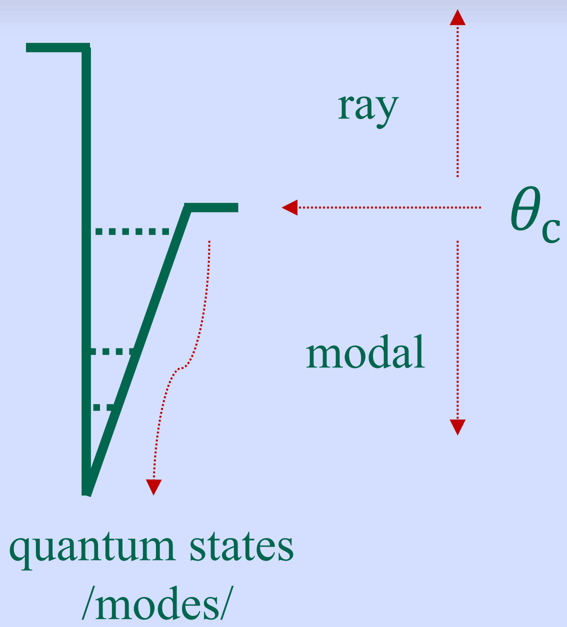
*The typical radial size of the main grazing mode*
*m=0 may essentially overcome the wavelength*




*The curvature increase, i.e. the decrease of the curvature radius, the propagating along the surface radiation is pushed out the capillary wall by surface potential*

# @ smooth channel surface: whispering gallery modes




*Transition from a single-mode propagation to a multi-mode one results in the increase of the angular divergence from $(\Delta\theta)_{min} < \theta_c$ to $(\Delta\theta)_{max} > \theta_c$, where $(\Delta\theta)_{max}$ is limited by the capillary system design.*

*Knowledge on quantum features of x ray reflection from curved surface helps in shaping low divergent beams… due to mixed modal radiation propagation*

# @ Resume: X & n

*Analysis of radiation propagation through capillary microguides has shown that all the observed features can be described within a theory of X-ray channeling, i.e.* **surface channeling in μ-size guides**

*The main criterion defining character of radiation propagation is the ratio between the transverse wavelength of radiation and the effective size of a guide, i.e.* **the ratio between the diffraction and Fresnel angles***:*

$$\lambda_\perp / d \equiv \vartheta_d / \vartheta_c$$

*@ this ratio is rather* **small**, *i.e. when the number of bound states is large, the* **ray optics** *approximation*

- **$\lambda_\perp \simeq$ d**, a **few modes** *will be formed in a quantum well;*
- **$\lambda_\perp \gg$ d** - *just a* **single mode** .

*@ all the considerations taken for X-rays is valid for* **thermal neutrons***.*

# @ capillary guiding of charged particles (i)

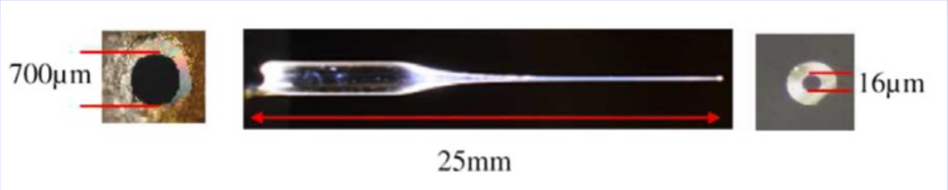
Since the first observations of the passage of ions through dielectric capillaries [*Stolterfoht, N., Bremer, J.H., Hoffmann, V., Hellhammer, R., Fink, D., Petrov, A., et al. Transmission of 3 keV Ne7+ ions through nanocapillaries etched in polymer foils: Evidence for capillary guiding. Phys Rev Lett 2002;88:133201*], this topic has attracted more and more attention of physicists. The phenomenon is explained by the fact that when the ion beam passes through the capillary, part of the beam first settles on the inner surface of the capillary and, accumulating there, creates a repulsive potential, which becomes a channel-guiding potential for a charged particle [*Schiessl, K., Palfinger, W., T˝ok´esi, K., Nowotny, H., Lemell, C., Burgd¨orfer, J.. Simulation of guiding of multiply charged projectiles through insulating capillaries. Phys Rev A 2005;72:062902*].

The undoubted interest in the development of new methods for controlling particle beams based on capillary systems have resulted in a wide spectrum of experimental activities dedicated to this phenomenon, while theoretical works counts disproportionally much less published articles (detailed review [*Stolterfoht, N., Yamazaki, Y.. Guiding of charged particles through capillaries in insulating materials. Physics Reports 2016;629:1–107* ] and Refs. therein).

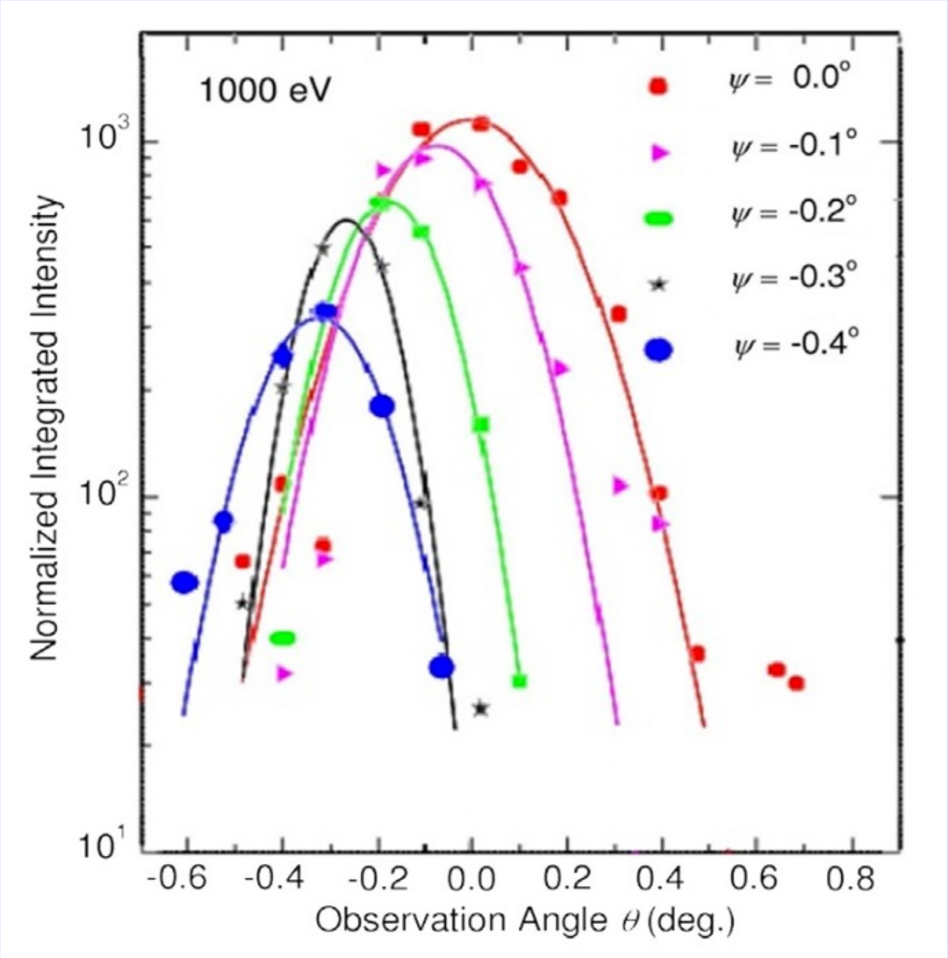
Known theoretical studies mainly aim at simulating the motion of charged particle beams inside capillary insulators using the Monte Carlo method [*Schiessl, K., Palfinger, W., Lemell, C., Burgd¨orfer, J.. Simulation of guiding of highly charged projectiles through insulating nanocapillaries. Nucl Instr Meth B 2005;232(1):228– 234*].

No references to the first Soviet results by Kumakhov & colleagues

# @ capillary guiding of charged particles (ii)




Borosilicate capillary with microscopic views of the inlet and outlet of the sample. Starting from the left-hand side, the capillary consists of a straight tube followed by an exponential and a conical shape.



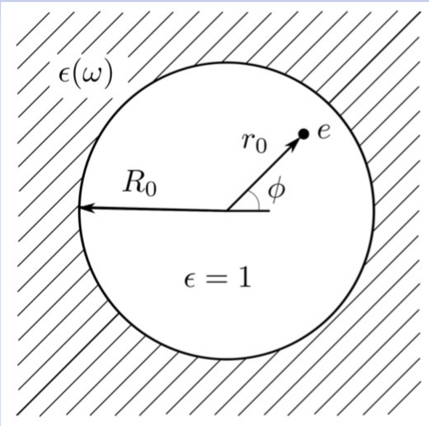

Significantly larger tilt angles than the aspect angle -> *the electrons must have interacted at least once with the capillary surface*

*The electron energy distribution proves mostly elastic scattering*

*Transmission profiles for $e^-$ 1 keV*


S. Wickramarachchi, B. Dassanayake, D. Keerthisinghe, A. Ayyad, J. Tanis, Electron transmission through a microsize tapered glass capillary, Nucl. Instrum. Methods Phys. Res. B 269 (2011) 1248–1252.

# @ surface channeling of capillary-guided charged particles




Scheme of a cylindric cavity of radius $R_0$ in the infinite dielectric, characterised by the permittivity ε(ω), with a particle of the charge e moving inside the cavity. For the cavity we choose ε = 1.

In absence of free currents and charges, based on Maxwell's equations, the Fourier components of the field scalar and vector potentials are defined by the following equation

$$\left(\nabla_\perp^2 + \frac{\partial^2}{\partial z^2} + \frac{\omega^2}{c^2}\epsilon(\omega)\right)\begin{pmatrix} \varphi_\omega \\ \mathbf{A}_\omega \end{pmatrix} = 0 \qquad \nabla\mathbf{A}_\omega - i\frac{\omega}{c}\epsilon(\omega)\varphi_\omega = 0$$

From the condition of continuity of the electric and magnetic fields components tangential to the inter-face, we derive the dispersion law k(ω) with x = kc/ω and α = $R_0$ω/c

$$\frac{x^2 n^2 (\epsilon-1)^2}{\alpha^2 (x^2-1)(x^2-\epsilon)} = \left[\sqrt{x^2-1}\frac{K_n'(\alpha\sqrt{x^2-\epsilon})}{K_n(\alpha\sqrt{x^2-\epsilon})} - \sqrt{x^2-\epsilon}\frac{I_n'(\alpha\sqrt{x^2-1})}{I_n(\alpha\sqrt{x^2-1})}\right]\left[\epsilon\sqrt{x^2-1}\frac{K_n'(\alpha\sqrt{x^2-\epsilon})}{K_n(\alpha\sqrt{x^2-\epsilon})} - \sqrt{x^2-\epsilon}\frac{I_n'(\alpha\sqrt{x^2-1})}{I_n(\alpha\sqrt{x^2-1})}\right]$$

α = $R_0/\lambda_s$ - the ratio of the capillary radius $R_0$ to the wavelength of surface excitations $\lambda_s$

α ≪ 1 -- only at ε(ω) = −1,
α ≫ 1 -- the solution in the form of a series expansion in powers of a small parameter (1/α)

# @ effective interaction potential

The potential energy of interaction with the atomic system of a dielectric can be calculated as the sum of Coulomb potentials, represented as a Fourier series split at the cut-off frequency $q_0$

$$U_{int}(\mathbf{r}) = \frac{4\pi}{V_g}\sum_{\mathbf{r}_j}\left(\underbrace{\sum_{\mathbf{q}>\mathbf{q}_0}\frac{e_p e_j}{q^2}e^{i\mathbf{q}(\mathbf{r}_p-\mathbf{r}_j)}}_{\textit{no averaging}} + \underbrace{\sum_{\mathbf{q}<\mathbf{q}_0}\frac{e_p e_j}{q^2}e^{i\mathbf{q}(\mathbf{r}_p-\mathbf{r}_j)}}_{\textit{collective surface excitations}}\right)$$

Inside a cylindrical hollow cavity

$$\hat{H} = \int \hat{\psi}^+(\mathbf{r},z)\left(-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r},z)\right)\hat{\psi}(\mathbf{r},z)d^2r dz + \hat{H}_s + \int \hat{\psi}^+(\mathbf{r},z)\hat{\Phi}(\mathbf{r},z)\hat{\psi}(\mathbf{r},z)d^2r dz$$

ψ - the particle field operator (fermion-operator),
Φ - the operator describing the particle interaction with the surface excitations (boson-operator)

The equation of transverse motion inside a cavity describes the channeled motion.

$$\left(-\frac{\hbar^2}{2m}\nabla_\perp^2 + \underbrace{\frac{1}{L}\int V(\mathbf{r}_\perp,z)dz}_{\textit{averaged potential}} + \underbrace{\Phi(k,r)}_{\textit{induced potential}}\right)u_{\mathbf{n}}(\mathbf{r}_\perp) = \hbar\omega_\perp^{\mathbf{n}}u_{\mathbf{n}}(\mathbf{r}_\perp)$$

# @ averaged & induced potentials

Averaged potential after integration depends only on the distance

$$(1/L)\int V(\mathbf{r}_\perp, z)dz \equiv \bar{V}(r).$$

When the equation for elastic processes is solved, we consider only the real part of induced potential, while the potential imaginary part leads to a finite lifetime for each quantum state

$$U_{ind}(r) \equiv Re\left[\Phi(v, r)\right]$$

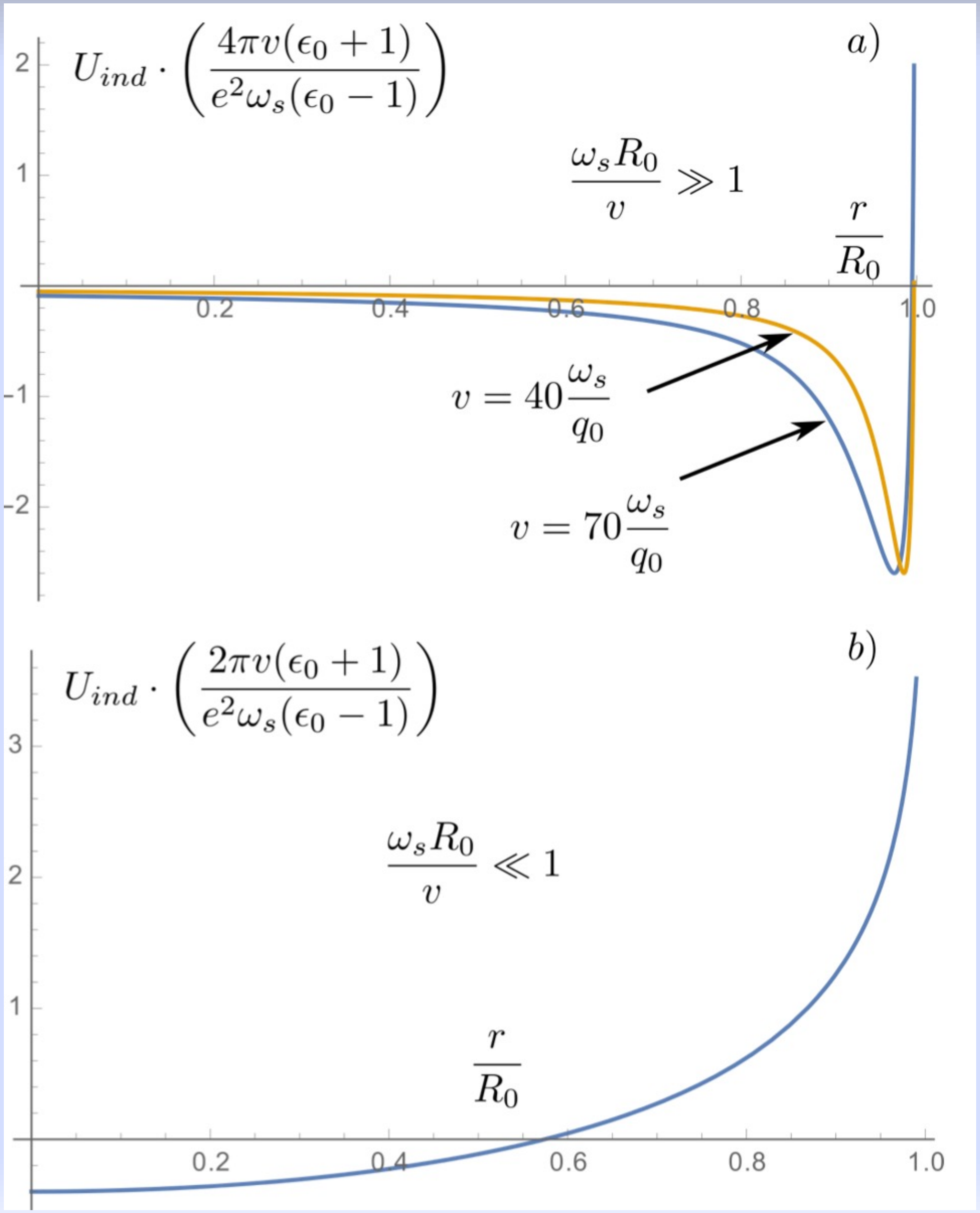
The effective potential for a channeled particle inside a cylindrical cavity is determined by the averaged and induced potentials

*@ the 1st - a continuous potential via known technique in channeling physics and does not result in any unexpected behaviours;*

*@ the 2nd - new features*

$$U_{ind}(r) = -\frac{e^2\omega_s}{2\pi v}\frac{\epsilon_0 - 1}{(\epsilon_0 + 1)}\times$$
$$\times \ln\left(\frac{q_0 v}{\omega_s} - 1\right)\ln\left(1 - \frac{r^2}{R_0^2}\right) + C$$

# @ induced potential



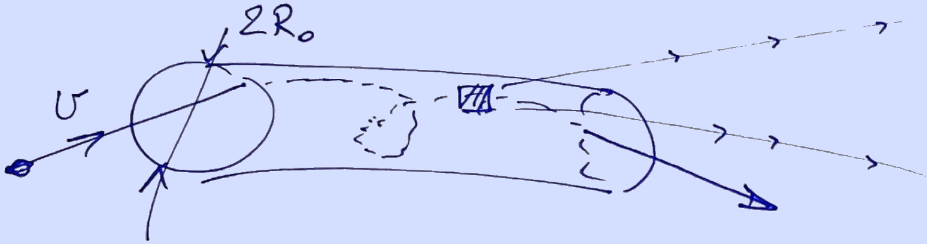

***Dimensionless induced potential versus the distance from the cavity axis.***

a). The graph at the condition $\omega_s R_0/v \gg 1$ shows two curves corresponding different values of longitudinal velocity. As seen, at the particle velocity increase the potential shape does not change, and the curve minimum tends to the cavity center.

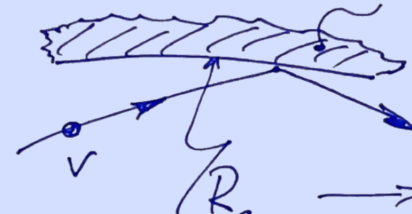
b). The general induced potential at $\omega_s R_0/v \ll 1$, while a concrete plotting is for $q_0 R_0 = 10^3$ and $\omega_s = 10^{15}$ $c^{-1}$ with the characteristic value $q_0 \sim 10^7$ $c^{-1}$ corresponding the cavity radius $R_0 \sim 10^{-4}$ cm.

# @ surface channeling for charged particles: simplified explanation

Small-angle close interactions




$\omega_s$ - plasmon energy




$R_{corr} \longrightarrow \in (R_{bend}, R_0)$

$R_{bend}$: ↑ max ↓ $\omega_{min}$; $R_0$: ↑ min ↓ $\omega_{max} \equiv \omega_0$

$v \oplus R_{corr} \rightarrow \omega$ for particle

particle → some kind of cyclotron frequency

$$(v/R) \equiv (v/R_{corr}) \xrightarrow[max]{} \frac{v}{R_0} \Rightarrow \omega_0 \rightarrow \omega_{max}$$

$$\frac{\omega_s R}{v} \equiv \frac{\omega_s}{(v/R)} \equiv \frac{\omega_s}{\omega} \vee 1 \rightarrow \text{'physical' limits:}$$

- $\omega_s/\omega \ll 1 \rightarrow$ for analysis $\omega_{max} \rightarrow \frac{v}{R_0} \rightarrow \omega_0$
- $\omega_s/\omega \gg 1$

a: $(\omega_s/\omega_0) \ll 1$ → scattering (elastic) by amorphous surface potential

b: $(\omega_s/\omega_0) \gg 1$ → surface plasmons more energetic ⇒ potential averaging
// induced potential with minimum ⟺ surface channeling

# @ Resume: charged particles

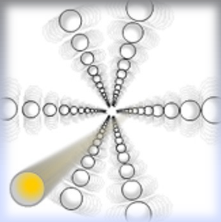
For the first time shown that at the limit

- $\omega_s R_0/v \ll 1$ the induced potential of interaction of a charged particle with the cavity surface acts as a scattering potential (forming a reflecting barrier);

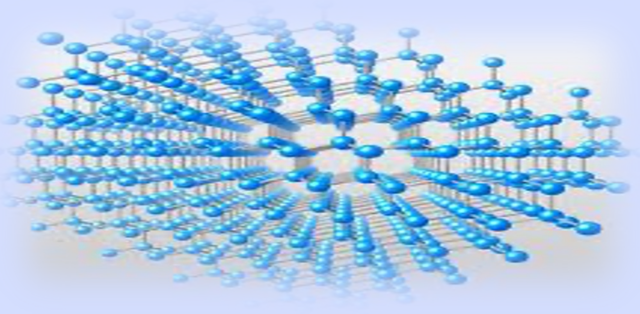
- $\omega_s R_0/v \gg 1$ it reveals a potential well near the surface.

The width of the potential well depends on the speed of the particle, i.e. the higher the speed of the particle the wider the well. In both cases considered, the real potential logarithmically tends to plus infinity. The maximum value of the induced potential mainly depends on the particle charge and its longitudinal velocity.
The estimates performed show that the averaged atomic potential is much higher than that induced for one particle, while for a beam of many particles channeled in a capillary the maximum value of the induced potential is expected to be essentially different.

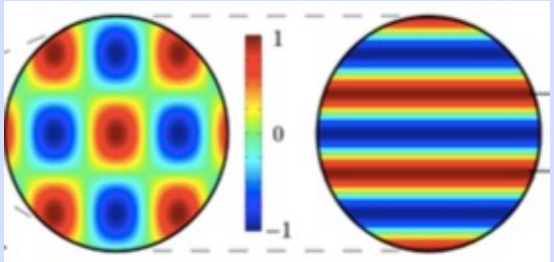
# Channeling based applications for Charged Beams: from Crystal to Capillary guides

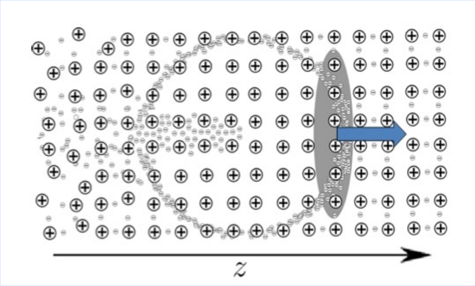


- **Crystal Channeling**
  - Beam shaping;
  - Micro-undulator;
  - Positron source

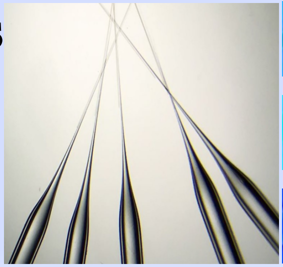


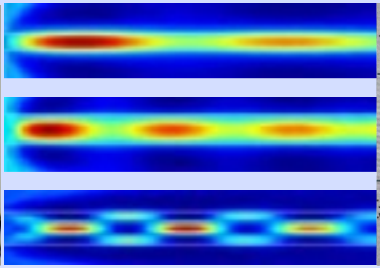
- **Laser & Plasma Channels**
  - Beam profiling for high current/luminosity;
  - Dynamics for wake field acceleration;

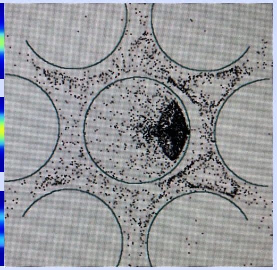



- **Capillary μ- and n-Channels**
  - beam redistribution;
  - Compact storage (?)





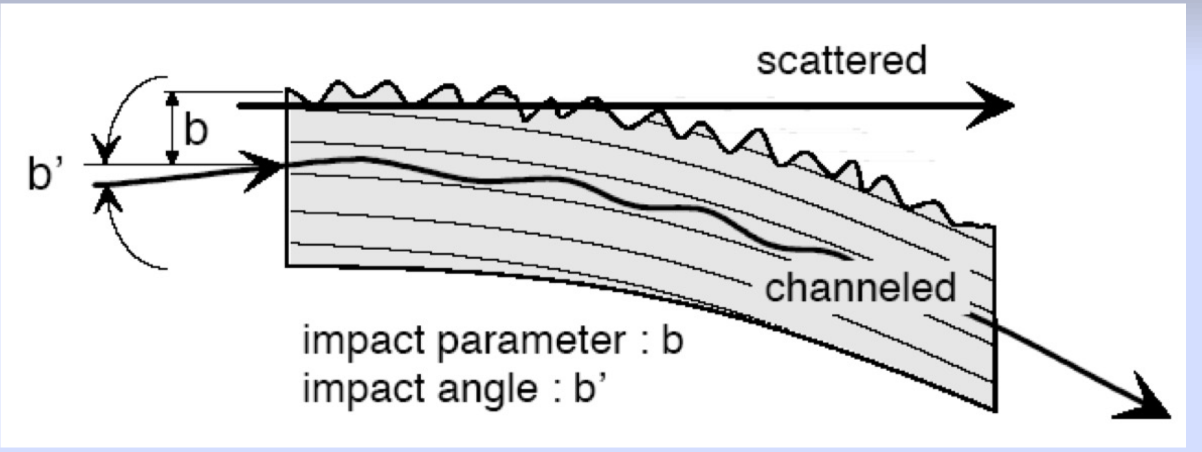


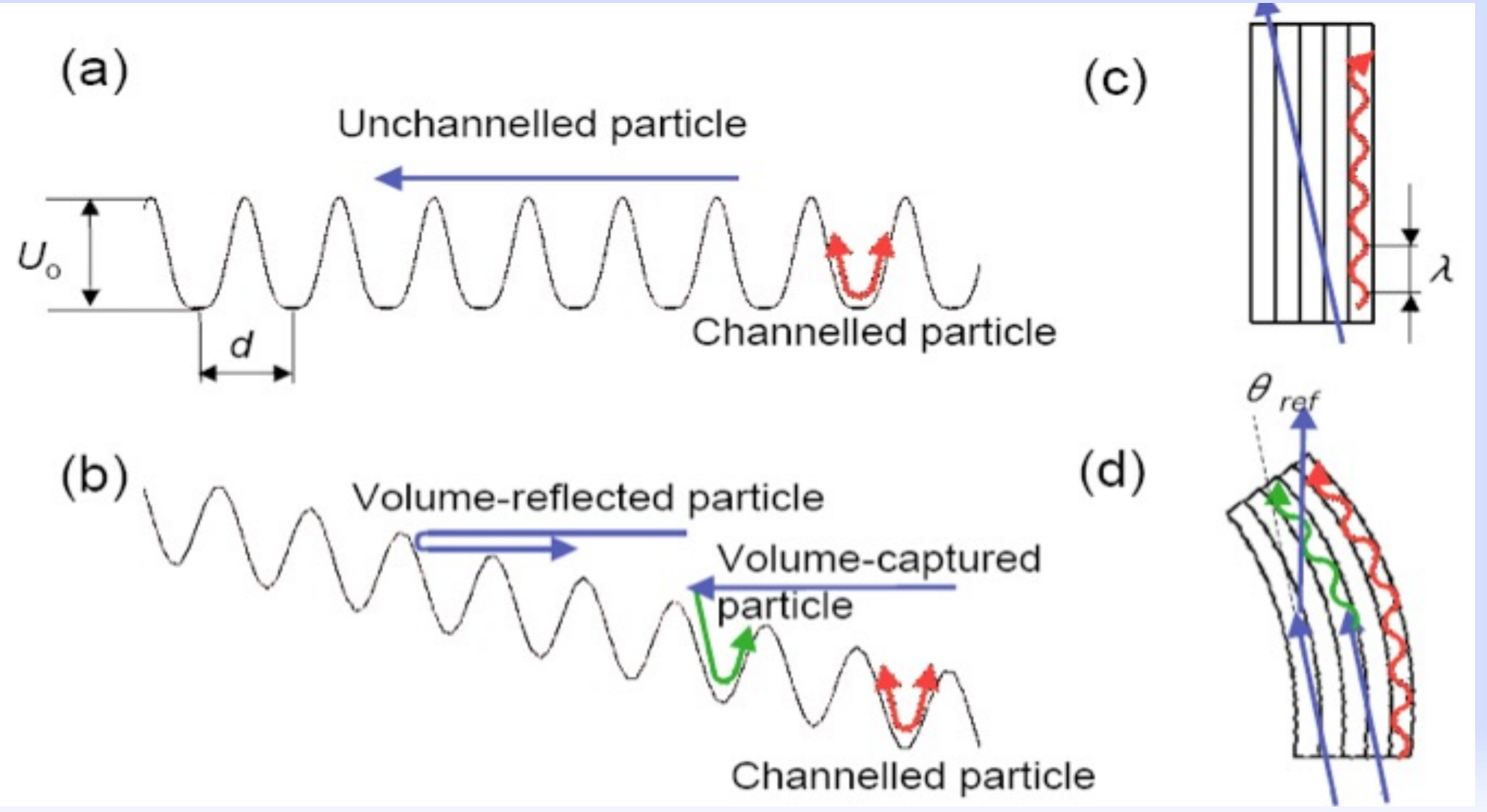
## @ Beam Steering & Coherent Radiation

# @ beam steering by crystal

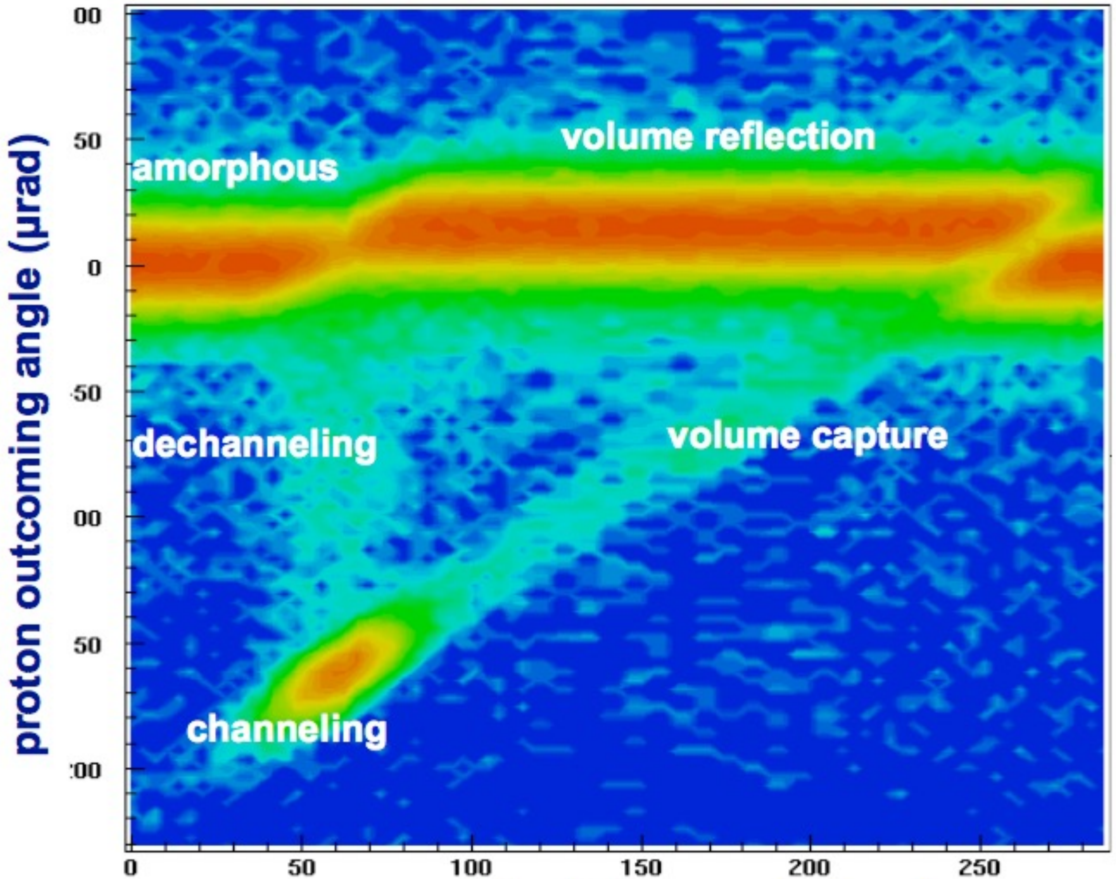
Possible processes:

- multiple scattering
- channeling
- volume capture
- de-channeling
- *volume reflection*

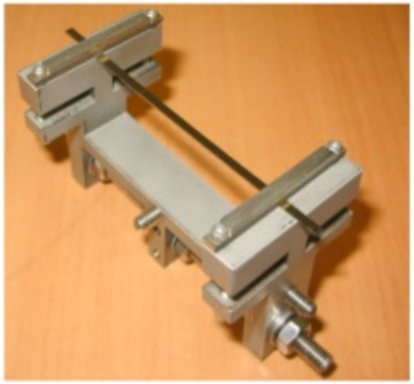


# @ first observation: 400 GeV/c CERN




**Single strip crystal**



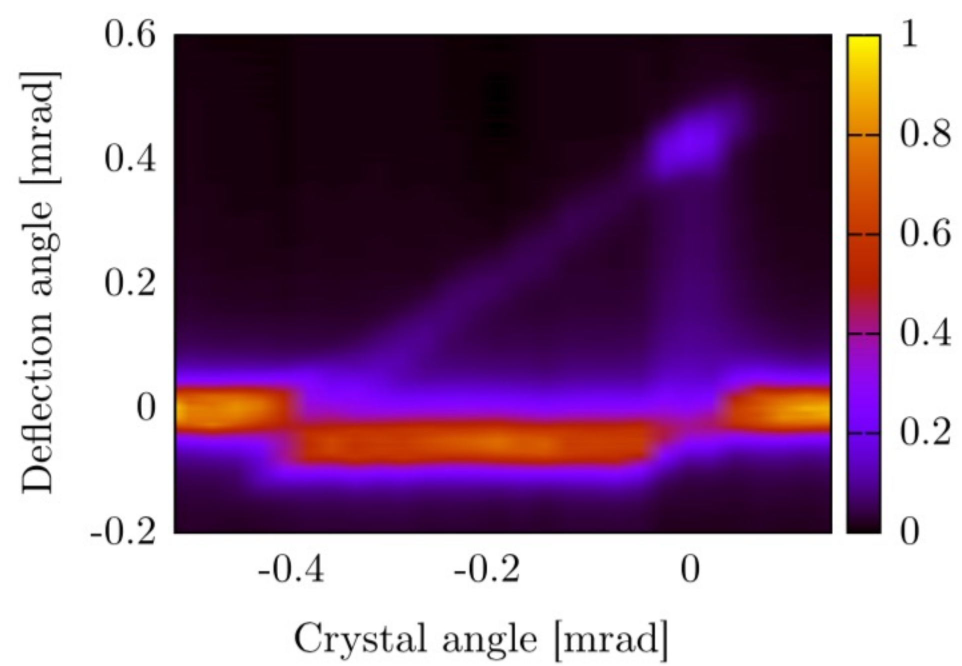
- *First measurement* of the volume reflection effect with a proton beam of 400 GeV/c

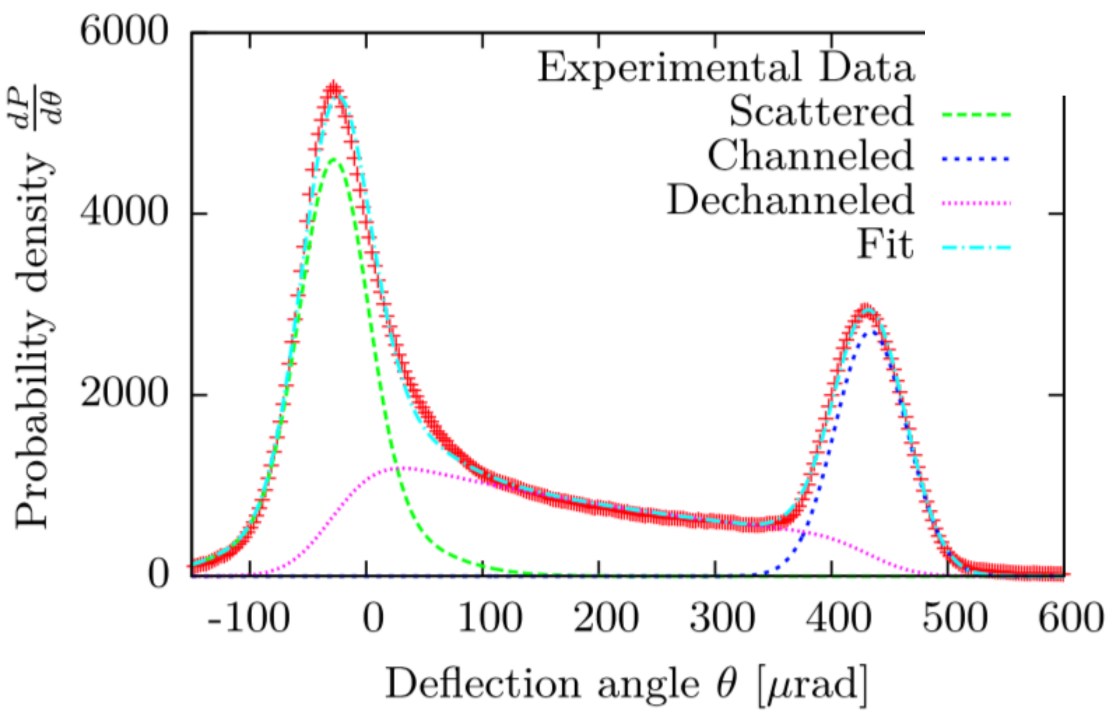
| EFFICIENCY | VALUE |
|---|---|
| VOLUME REFLECTION | 98.2 ± 0.1% |
| CHANNELING | 51.2 ± 0.7% |
| VOLUME CAPTURE | 1.3 ± 0.1% |
| DECHANNELING | 5.0 ± 0.4% |

**Multi-strip technique is under strong investigation /several assembled crystal**

# @ ultra-high γ beam steering: 10.5 GeV $e^-$ SLAC

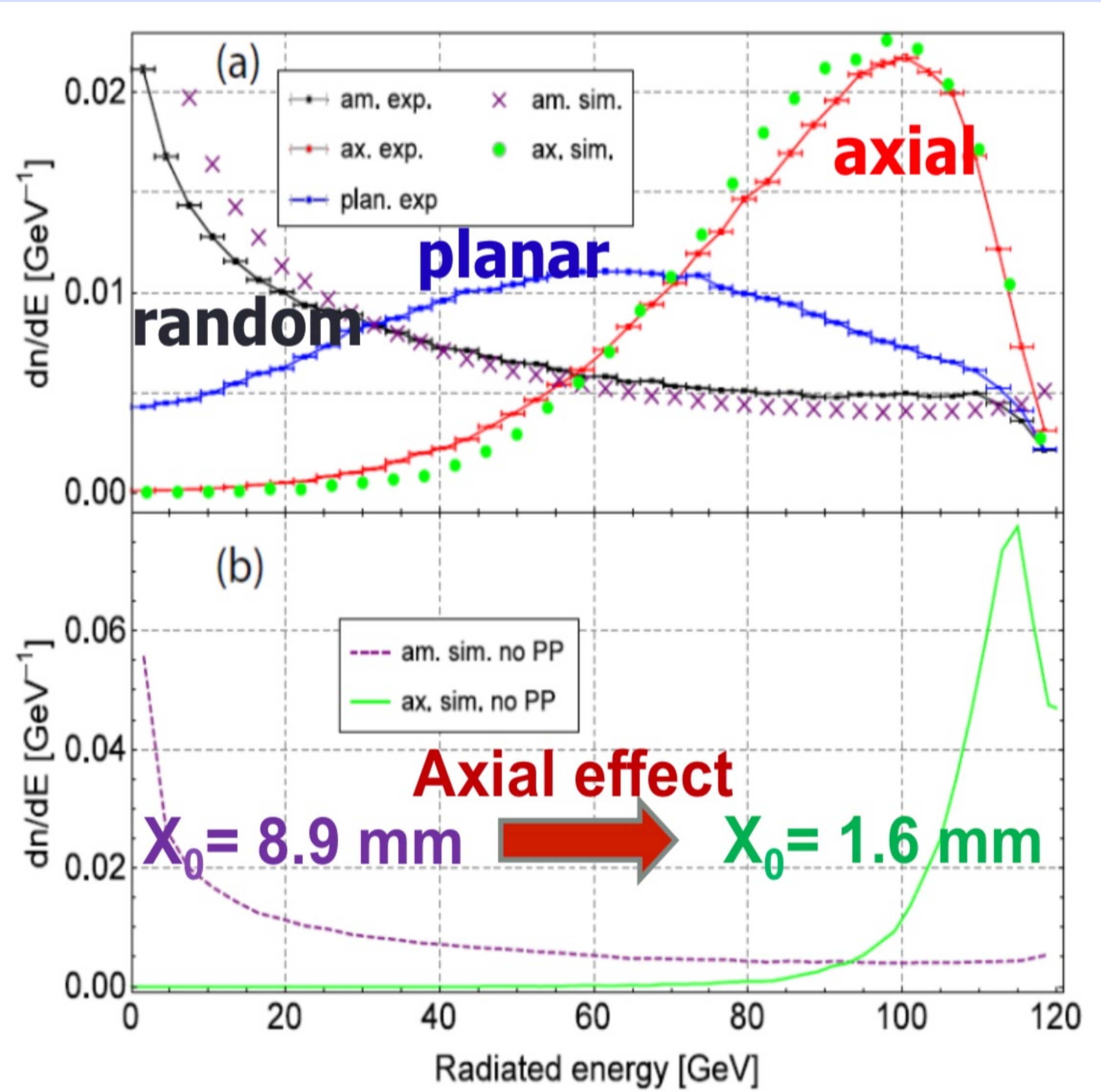
Deflected beam angular distribution



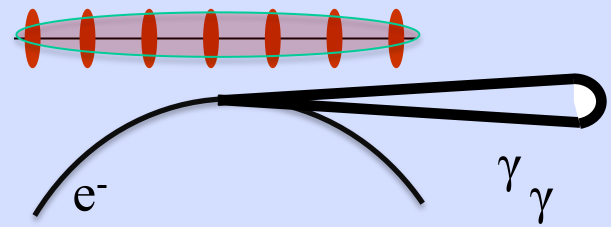




Distribution at channeling orientatio

# @ strong radiation regime at channeling: 120 GeV e⁻ CERN




PWO –
lead tungstate $PbWO_4$ crysta
4 mm




- Synchrotron-like radiation at channeling

$\gamma >> 1 \rightarrow \Sigma N \rightarrow N_{eff} >> N$
scattering by "single atom"

- Strong reduction of radiation length

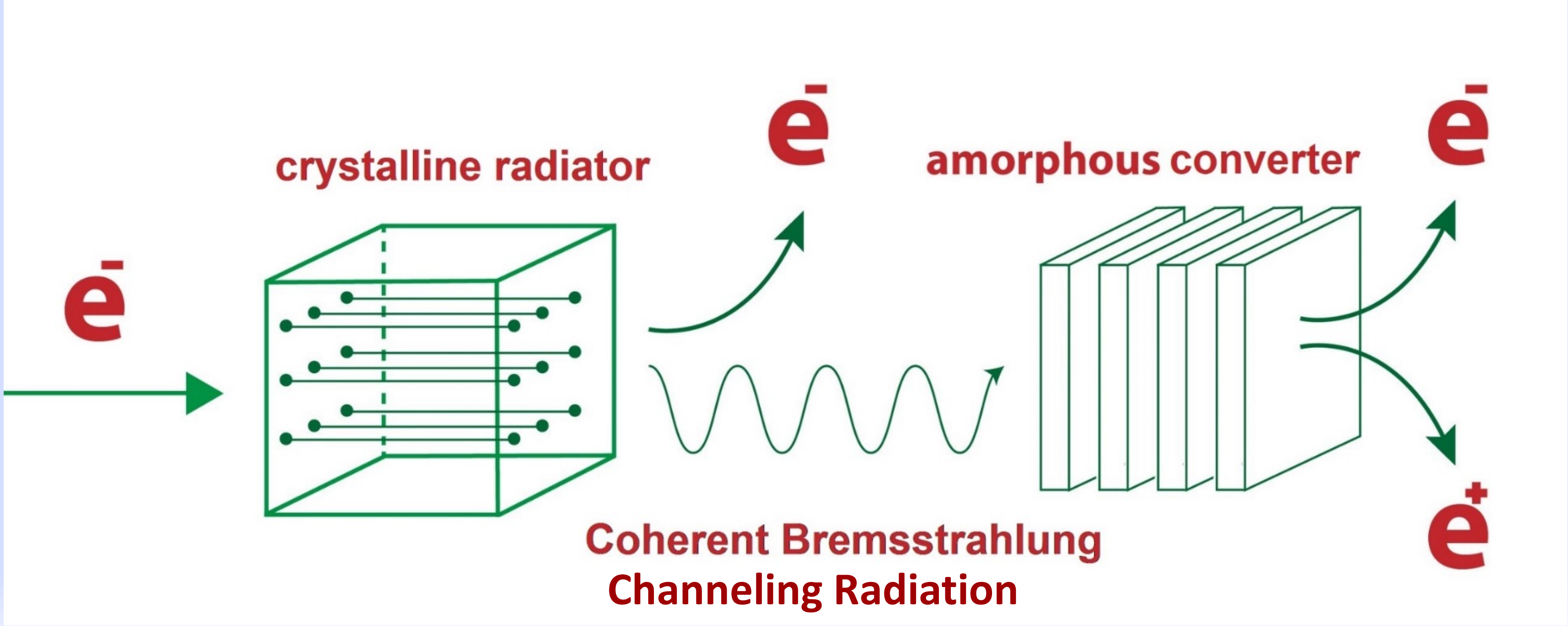
Courtesy of Bandier

# @ hybrid scheme for crystal based positron source

- Undulator+converter
- The scheme of hybrid positron source using CR or CB from primary electron beam

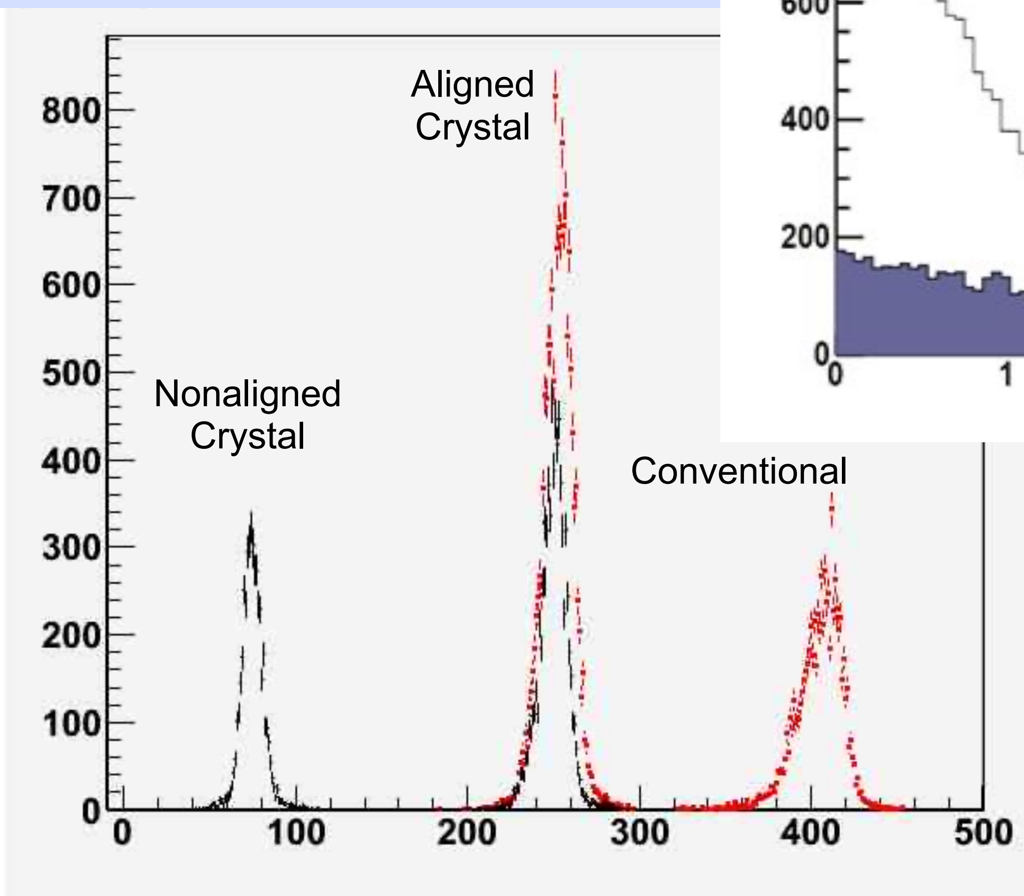
**Channeling Radiation** – efficient for sub GeV – essential increase for higher electron energy **200 MeV – and higher**

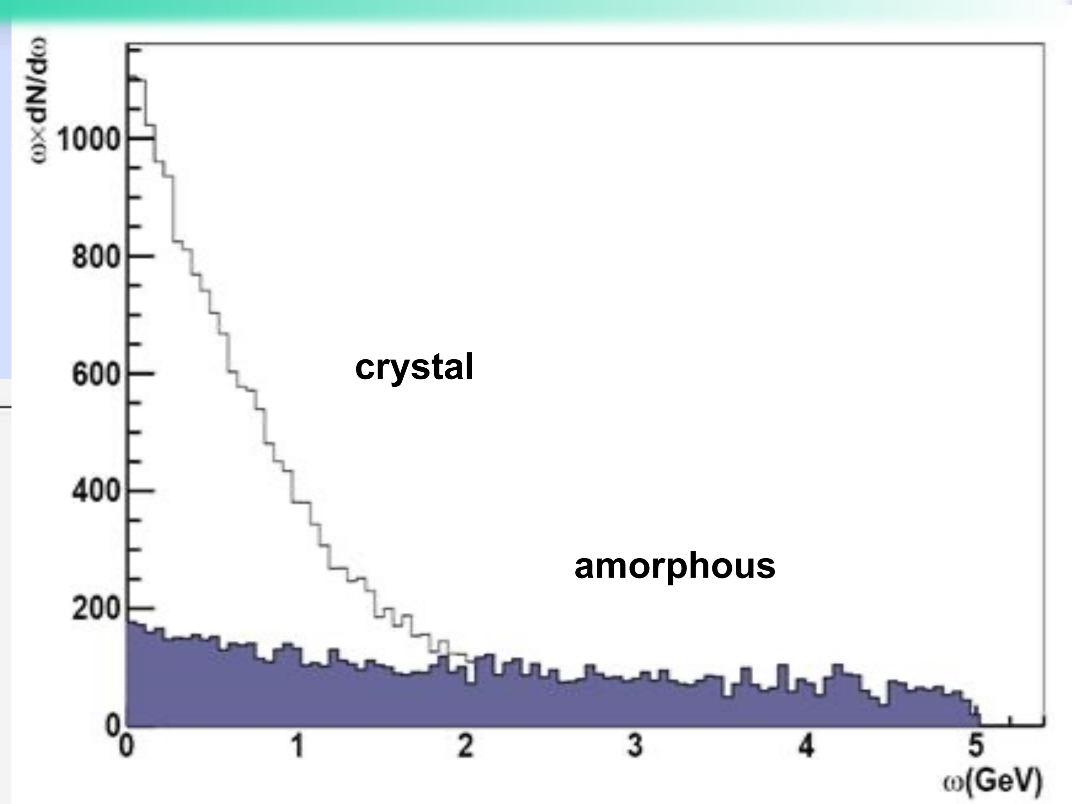
**Coherent Bremsstrahlung** – efficient even for MeV energies **10 – 100 MeV**



# @ channeling radiation at axial e- channeling in W

e+ yield for aligned
and misaligned crystals

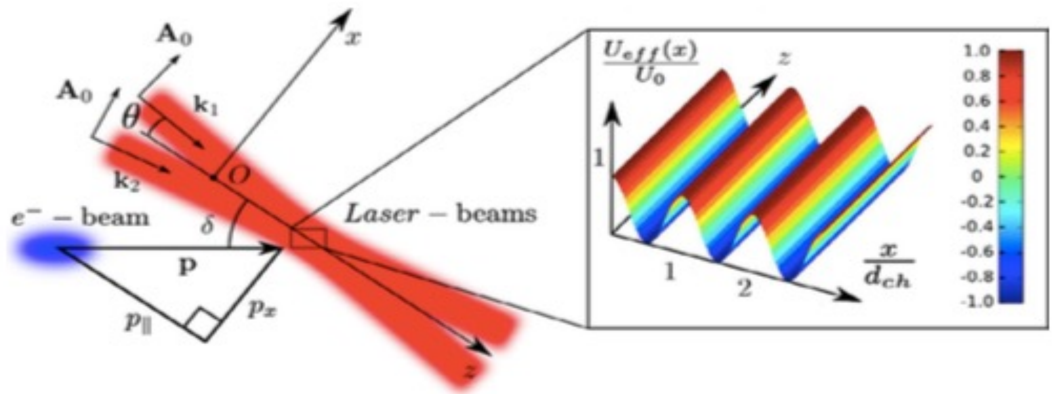



intensity of γ-ChR becomes much higher over B with primary $e^-$ energy increase

# @ Laser Channels → Optical Lattice

# @ channeling in OL




## Equation for slow motion particle wave function

$$i\hbar\frac{\partial\bar{\psi}}{\partial t} = \left(-\frac{\hbar^2}{2\gamma_{\|} m}\nabla^2 + U_{eff}\right)\bar{\psi}$$

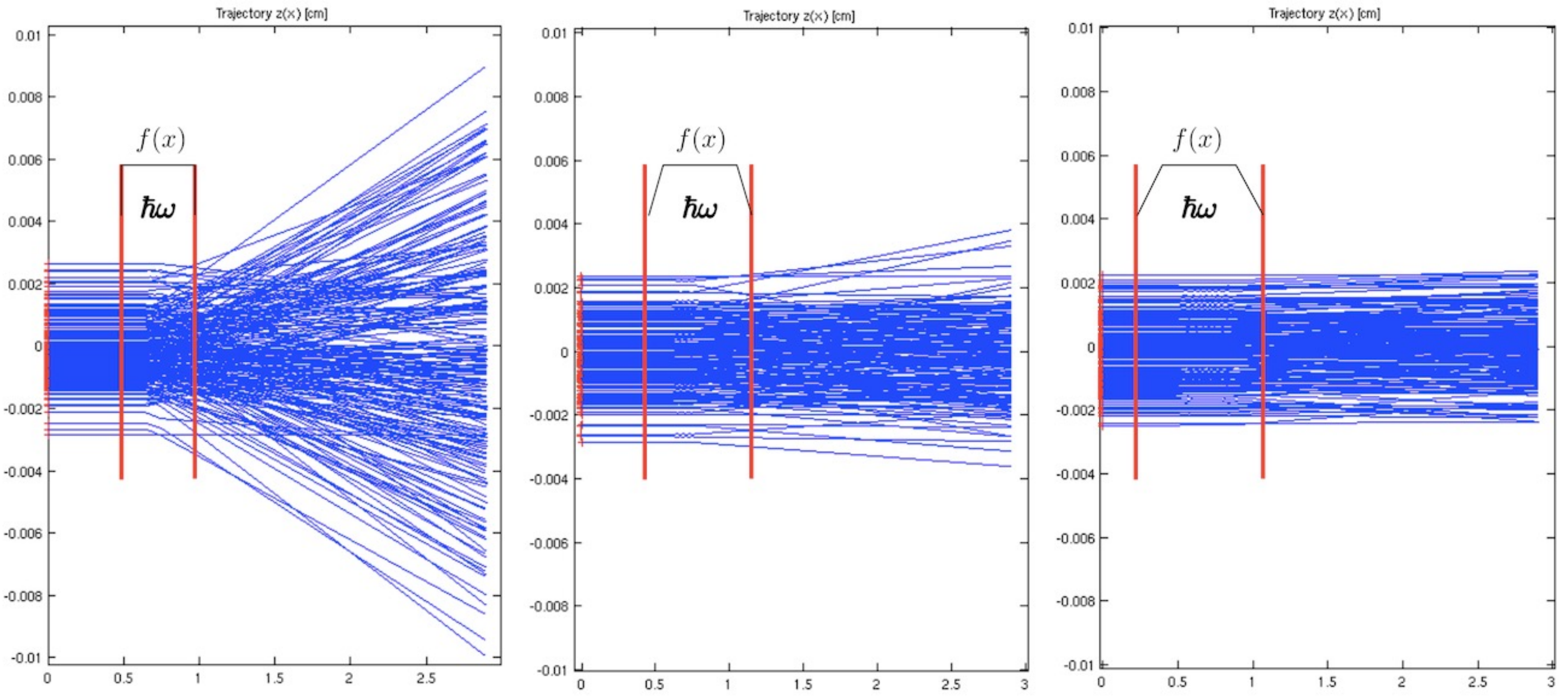
## Effective potential[1]

$$U_{eff} = \frac{e^2 A_2^2}{4\gamma_{\|} mc^2} - \frac{\hbar^2}{2\gamma_{\|} m}\overline{(\nabla \ln\chi)^2} - \frac{i\hbar e}{\gamma_{\|} mc}\overline{(\mathbf{A}, \nabla \ln\chi)} +$$

$$+\frac{\hbar^2}{2\gamma_{\|} mc^2}\left[\overline{\left(\frac{\partial}{\partial t}\ln\chi\right)^2} - 2\beta_{\|} c\,\overline{\frac{\partial}{\partial t}\ln\chi\frac{\partial}{\partial\zeta}\ln\chi} + \beta_{\|}^2 c^2\overline{\left(\frac{\partial}{\partial\zeta}\ln\chi\right)^2}\right]$$

here $\zeta = z - \beta_{\|} ct$, $\omega = \omega_0 - \beta_{\|} k_z$ - oscillation frequency of $\chi$, $A_2$ - slowly changing term of the field $\mathbf{A}$, $U_{eff}$ - complex function, $\mathrm{Im}\,U_{eff} \sim \frac{e^2 A^2}{(\gamma_{\|} mc^2)^2}(\nabla\bar{\psi})^2$

# @ optical lattice time structure for beam profiling

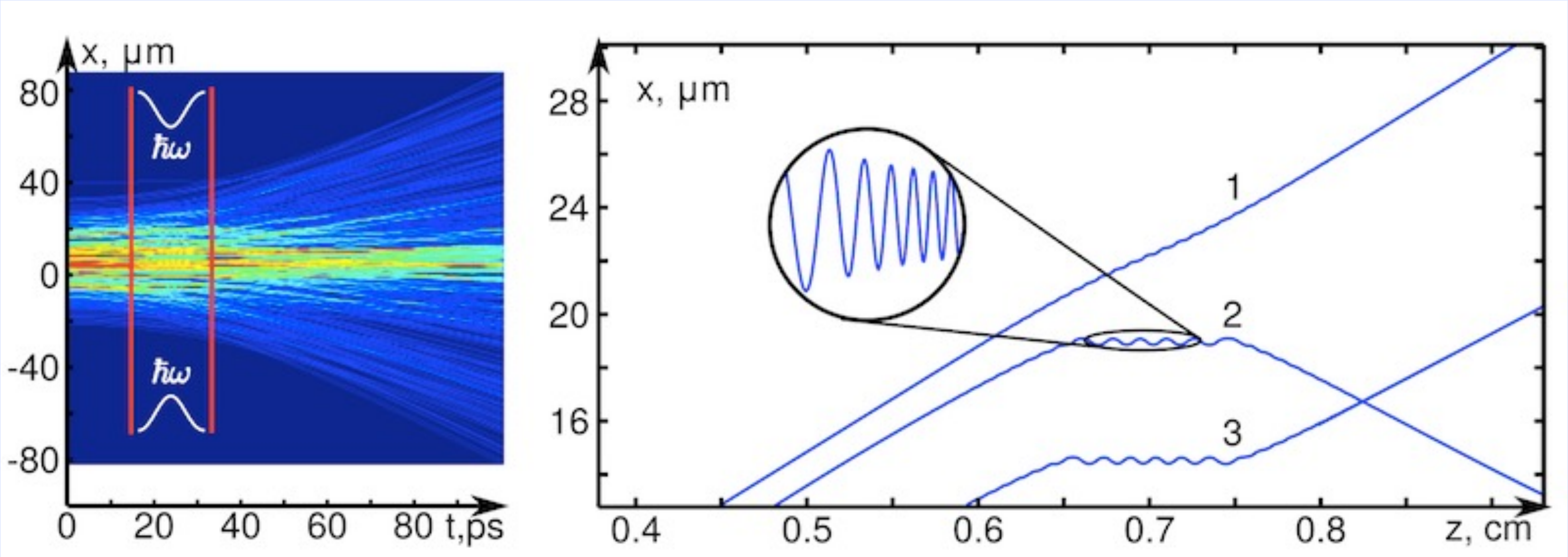



Scattering - defocusing

Focusing

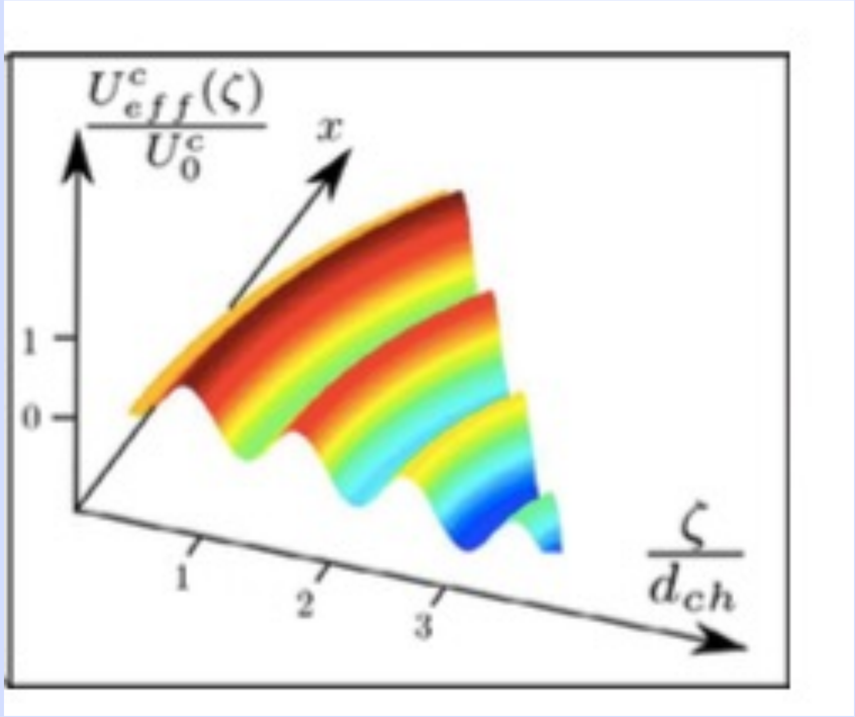
Condensing

# @ beam flux-peaking vs space charge




Numerical simulations (presented above) show that 0.8 pC 1.9 MeV Gaussian electron beam with zero initial divergence might be partially trapped by optical lattice, formed by two counter propagating laser beams with electrical field intensity $10^5$ CGS units each. The laser beams have Gaussian transverse profile with $\sigma_z$=1mm and are positioned at 23 ps from initial beam position. Density color plot of the beam passing through optical lattice (left) depicts particle distribution over time. While the majority of electrons was trapped by optical lattice potential channel, there were some with transverse energy big enough to escape from it

# @ effective potential of curved laser channels




$$\rho_{cr} = \frac{4(m\bar{\gamma}c^2)^2}{e^2 A_0^2 k\psi} \approx 1.6 \cdot 10^{-8} \left(\frac{m\bar{\gamma}c^2}{e}\right)^2 \frac{\omega_0}{\psi I}$$

critical radius for e- steering
in curved laser field

$$U^c_{eff}(\bar{\zeta}) = \frac{e^2 A_0^2}{8mc^2\bar{\gamma}} \cos\left(2k\psi\bar{\zeta}\right) - \frac{\bar{\gamma} m v_0^2 \bar{\zeta}}{\rho_0}$$

effective potential of curved laser channel

# @ radiation features

The photon radiated frequency of spontaneous particle transition from state ($\sigma_i$ ,$n_i$) to state ($\sigma_f$ ,$n_f$) has the same form as in classical description ($\sigma$,n-quantum number of channeling motion and number of absorbed photons) :

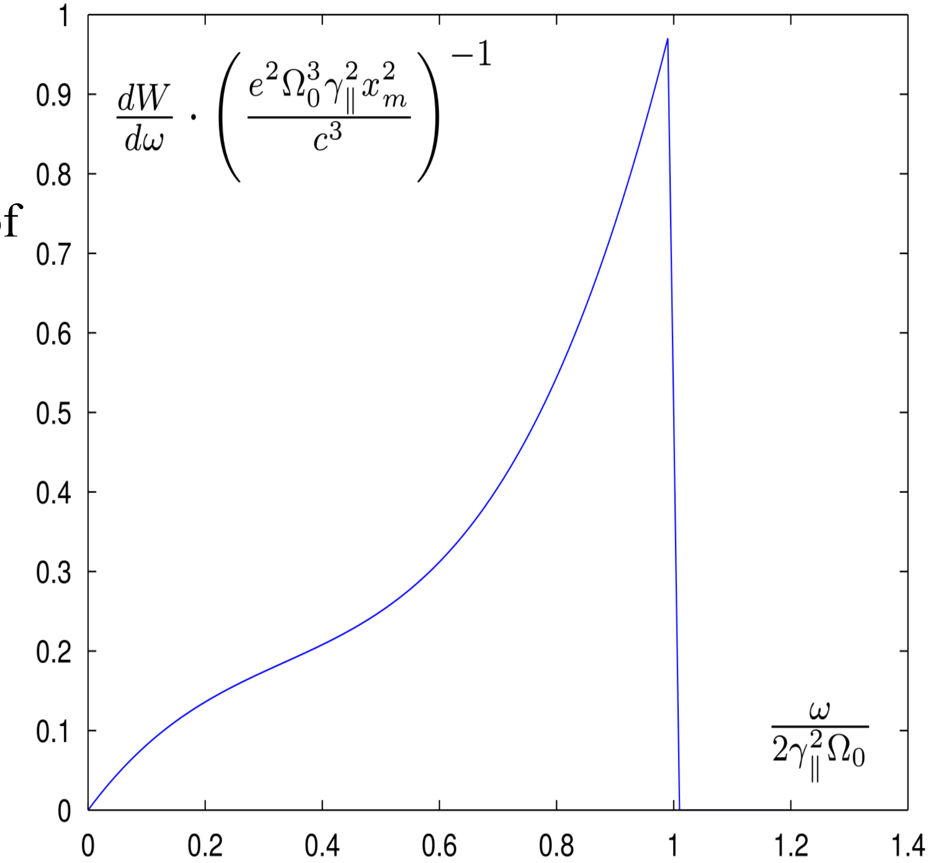
$$\omega_\lambda = \frac{(n_i - n_f)\omega_1}{1 - \beta_\parallel \cos\theta} + \frac{(\sigma_i - \sigma_f)\Omega_0}{1 - \beta_\parallel \cos\theta}$$

$$\omega_1 = \omega_0(1 - \beta_\parallel \sin\alpha)$$

Frequency of small fast oscillation of classical particle

$$\omega_\lambda = \frac{(\sigma_i - \sigma_f)\Omega_0}{1 - \beta_\parallel \cos\theta}, \quad n_i = n_f$$

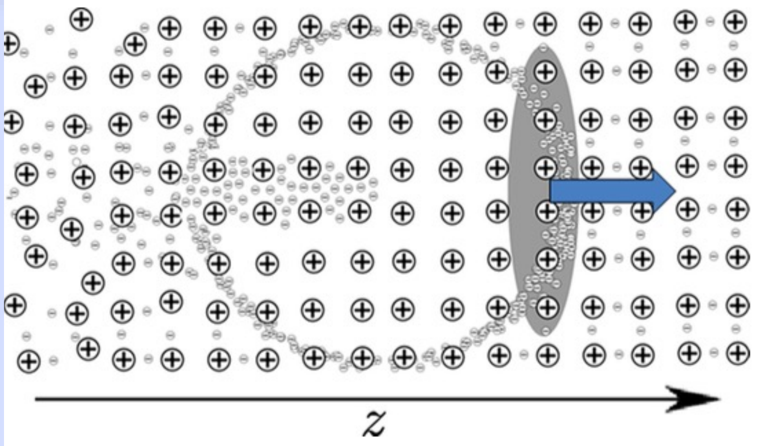
Channeling radiation frequency




Channeling radiation spectra has the same form as a classical particle in dipole approximation

classical → $x_m^2 = \hbar\sigma/(2\gamma_\parallel m\Omega_0)$ ← quantum

# @ laser based plasma channel: i




*buble propagates creating behind a positively charged channel*

$$\frac{dp_z}{dt} \approx -2\pi e^2 n_0 (z - v_l t),$$
$$\frac{d\mathbf{p}_\perp}{dt} \approx -2\pi e^2 n_0 \mathbf{r}_\perp,$$

$$\begin{cases} \mathbf{A} \approx 0, \\ \varphi = -\pi n_0 e r_\perp^2 \end{cases}$$

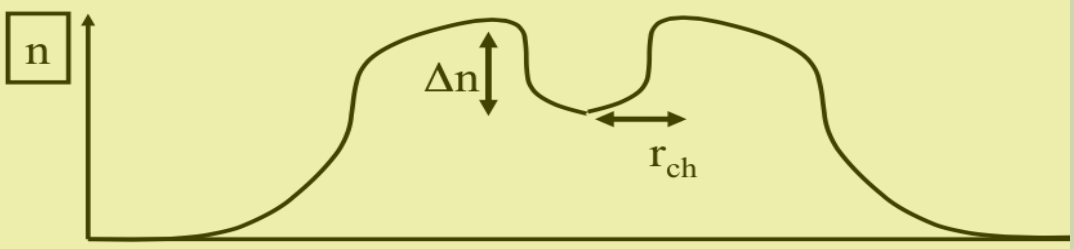
*for an infinite cylindrical channel containing 'frozen' ions*

*relativistic electron motion*

*down to the ion channel*

$$H = E_z + \frac{c^2 p_\perp^2}{2E_z} - e\varphi$$

$$E_z = c\sqrt{p_z^2 + m^2c^2}$$




$$w_0 = \left[ r_{ch}^2 / (\pi r_e \Delta n) \right]^{1/4}; \;\; r_e = e^2 / mc^2$$

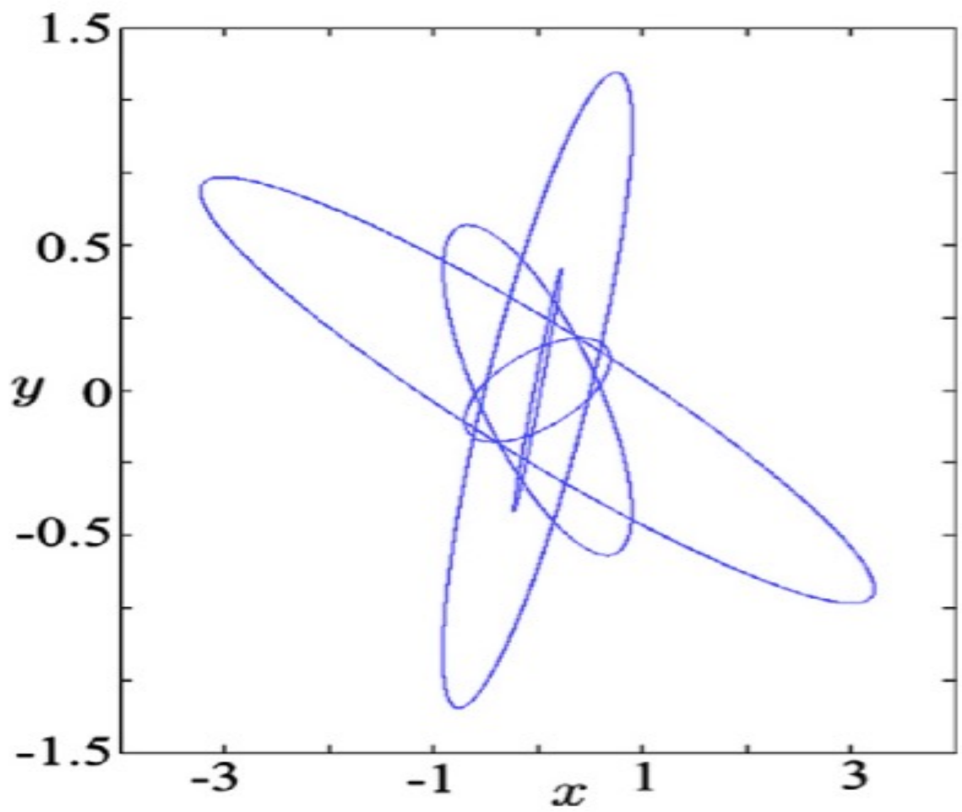
# @ laser based plasma channel: ii

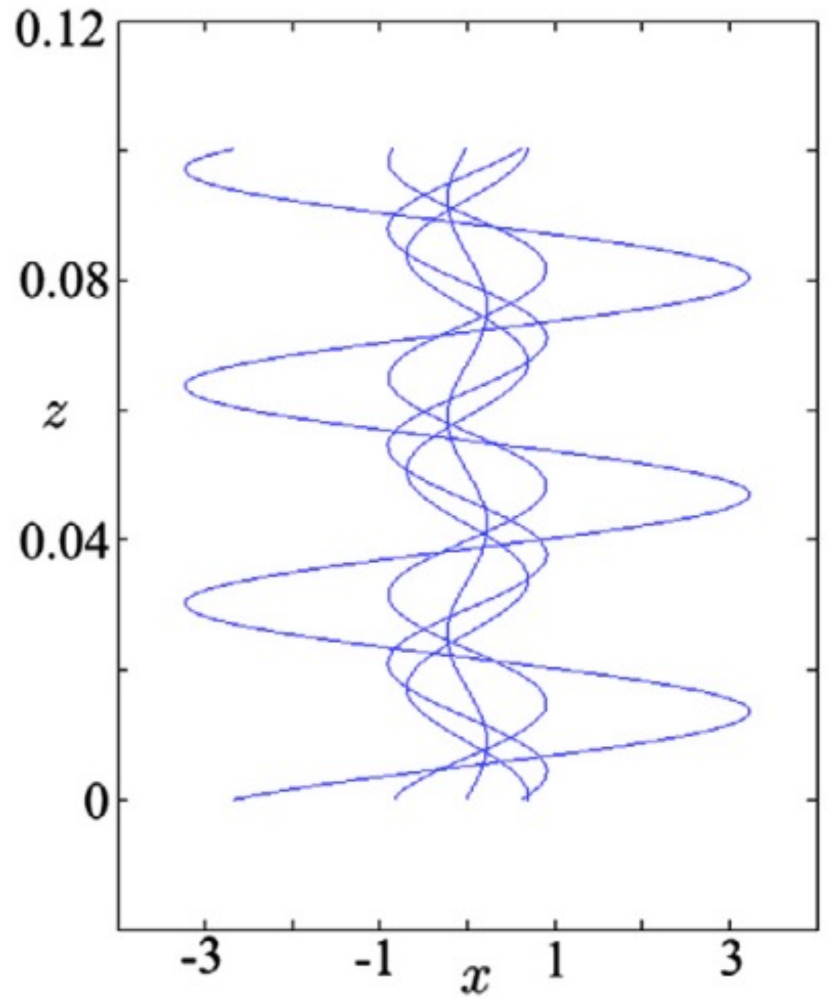
*...channeling method simplifies calculations*

*trajectory of a plasma channeled particle*

$$z(t) = at + b\sin(2\omega_0 t + \alpha), \quad \mathbf{r}_\perp(t) = \mathbf{r}_0 \cos(\omega_0 t) + \mathbf{v}_0 \sin(\omega_0 t)/\omega_0$$

$$\omega_0^2 = \frac{2\pi e^2 n_0 c^2}{E_z}$$



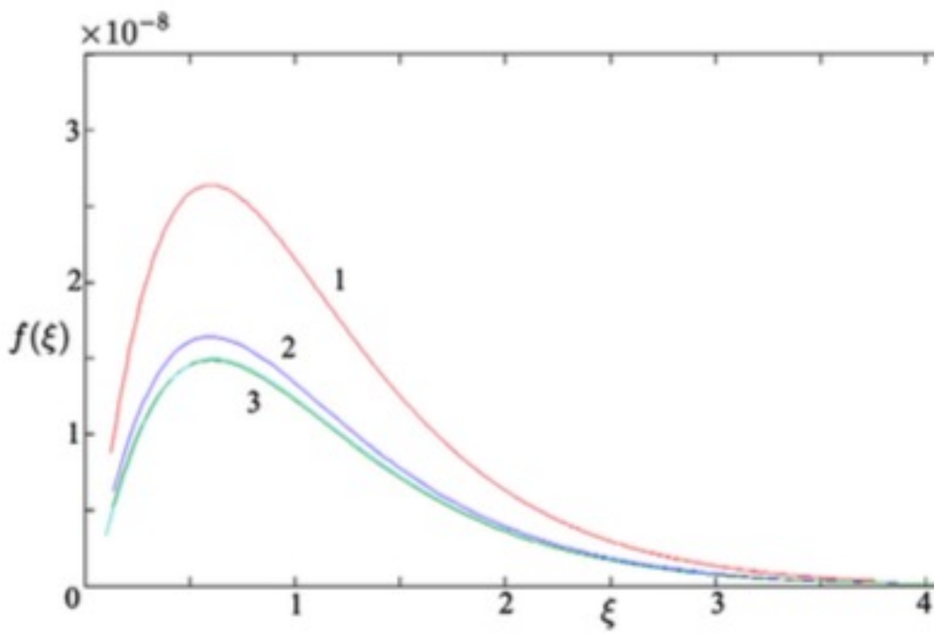



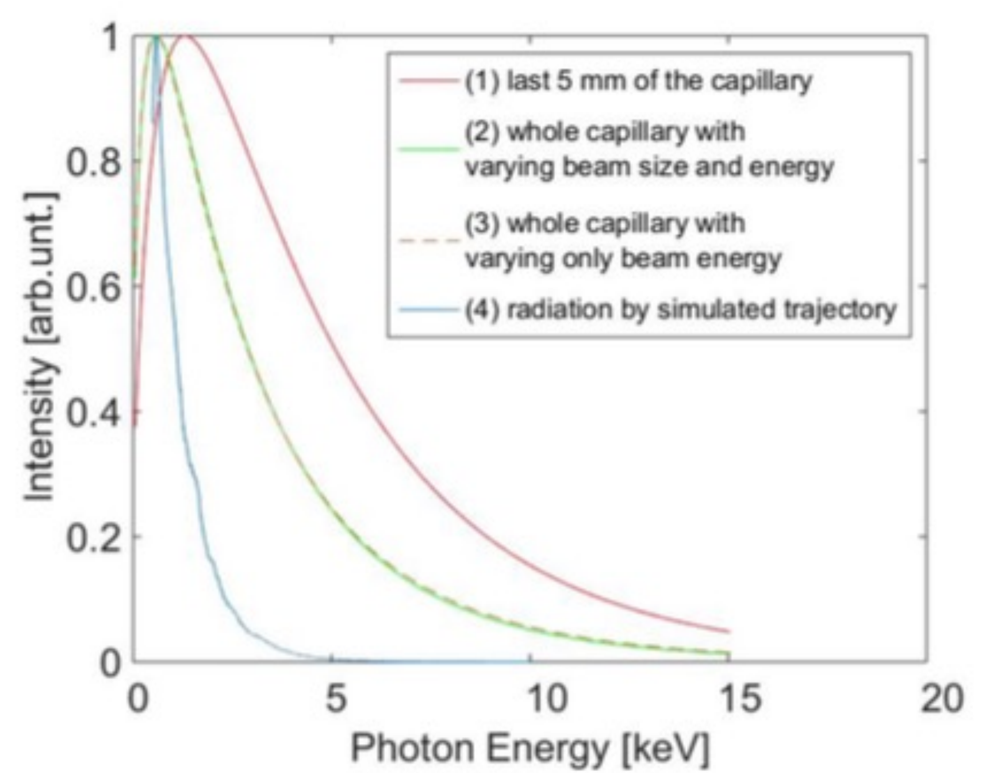
# @ laser based plasma channel: radiation

$$\frac{dI(\theta=0)}{d\omega} = \frac{e^2\gamma_z^4\omega'^2}{3\pi^3 c\omega_0}\left(\frac{3\omega_0}{\omega'}\right)^{2/3} f\left(\frac{\omega}{\omega'}\right),$$

$$f(\xi) = \xi^2\left((2a_1+a_2)\left(K_{1/3}(\xi) - \left(\frac{3\omega_0}{\omega'}\right)^{1/3} K_{2/3}(\xi)\right)K_{1/3}(\xi) + a_1\left(\frac{3\omega_0}{\omega'}\right)^{2/3} K_{2/3}^2(\xi)\right),$$

$$a_1 = \frac{r_0^2\omega_0^2 + v_0^2}{4c^2}, \quad a_2 = \frac{r_0^2\omega_0^2 - v_0^2}{2c^2}\cos\alpha + \frac{\omega_0(\mathbf{r}_0, \mathbf{v}_0)}{c^2}\sin\alpha, \quad \omega' = 3\gamma_z^3\omega_0\sqrt{a_1},$$

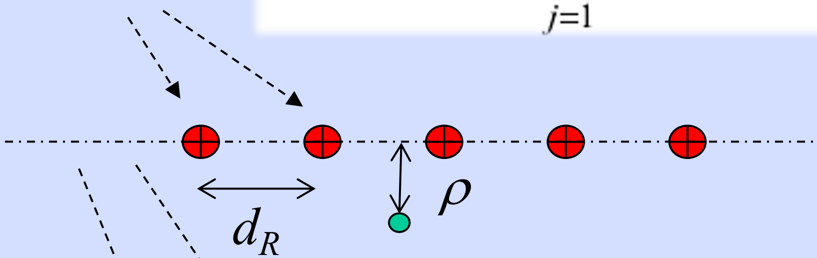


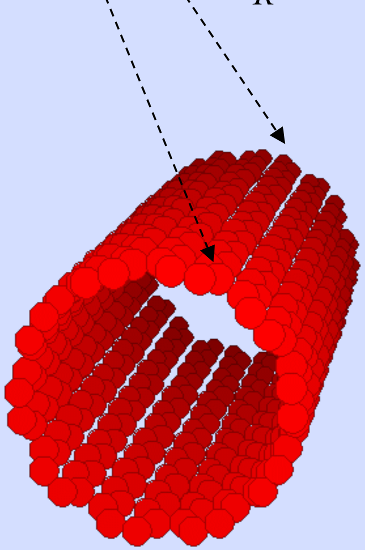
## @ Capillary Micro- & NanoChannels

# @ channeling in nanotubes

$$f(\mathbf{k}) = 4\pi Ze \sum_{j=1}^{N} a_j \exp(-k^2/4b_j^2)$$ - *form-factor for the separate fullerene*




$$V_R(\rho) = (4Ze^2/d_R) \sum_{j=1}^{N} a_j b_j^2 \exp(-b_j^2 \rho^2)$$



$$U(\mathbf{r}) = \sum_{i} V_R(|\ \mathbf{r} - \mathbf{r}_i\ |)$$

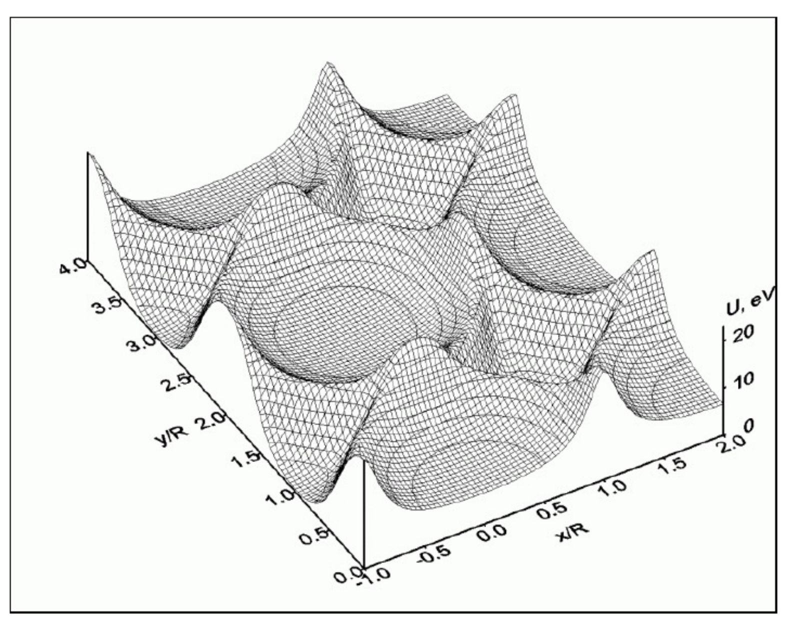
*continuum potential*
*as sum of row potentials*

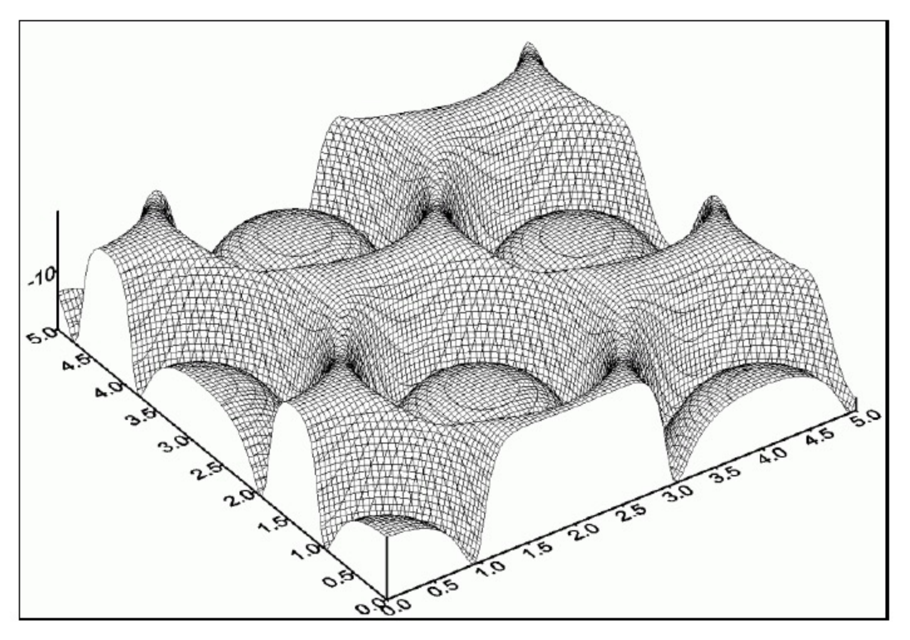
$$U(r) = (16\pi dZe^2/3\sqrt{3}\,l^2) \sum_{j=1}^{N} a_j b_j^2 \exp\{-b_j{}^2[r^2 + (d/2)^2]\} I_0(b_j^2 rd)$$

*r – distance from the tube*
*$I_0(x)$ – mod. Bessel function*

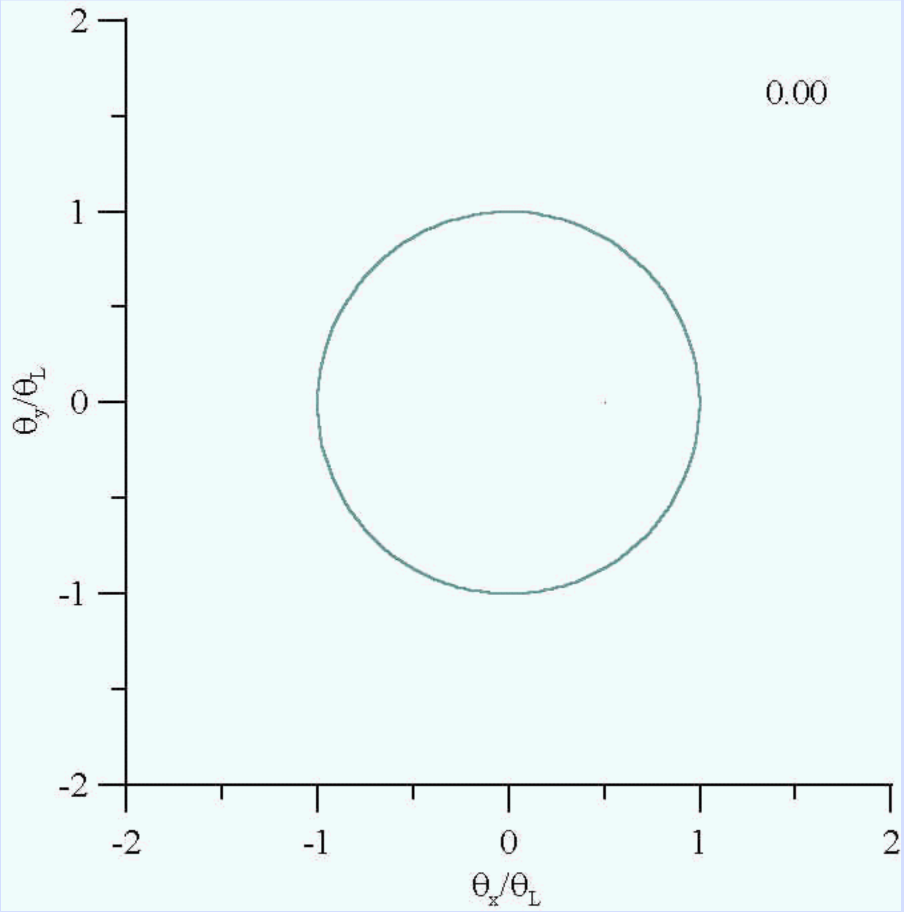
# @ continuous potentials: Doyle-Turner approximation

*Continuum potential in C60 fullerite: [100] and [110] after averaging of the wall potential*

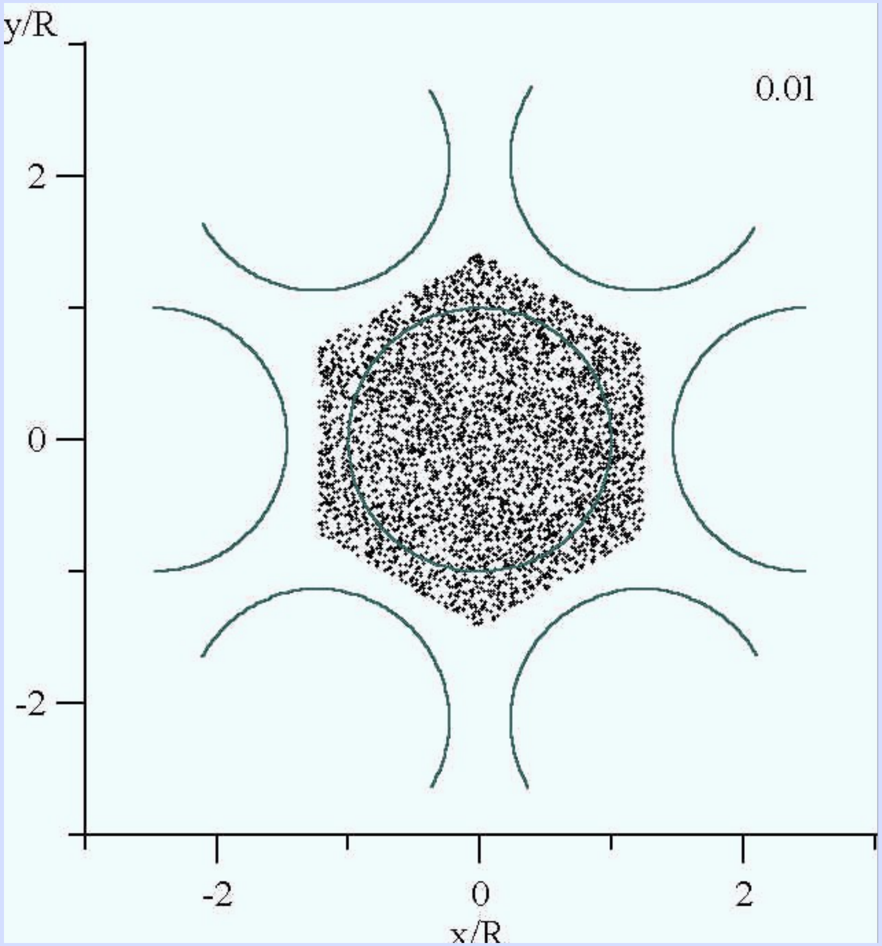


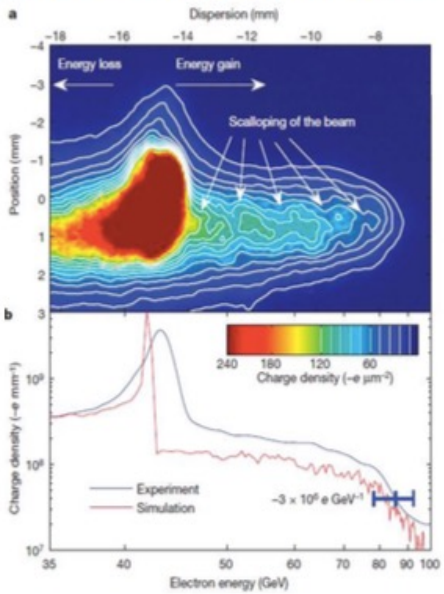
# @ simulations for nanotube channeling: *angular distribution*



# @ simulations for nanotube channeling: *spatial distribution*



## Gas-State Plasma



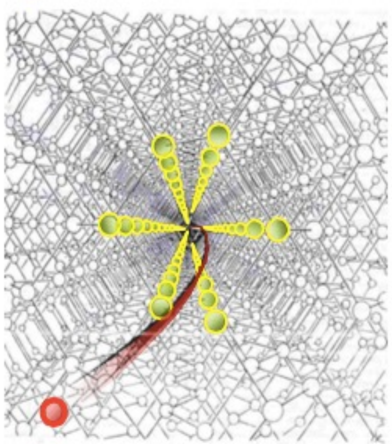

$10^{16} – 10^{18} cm^{-3} \rightarrow 10 \sim 100$ GeV/m

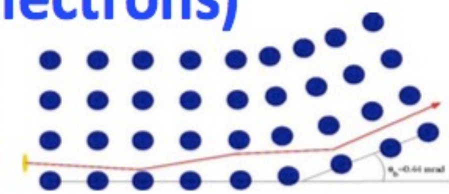
Nature 445, 741-744 (2007)

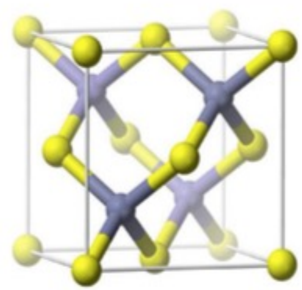
Energy Doubling: ~ 52 GV/m (@ 42 GeV)

## Solid-State Plasma (Conduction Electrons)

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$







**$10^{20} – 10^{23} cm^{-3} \rightarrow 1 \sim 30$ TeV/m**

*courtesy of Shin*

# @ channeling for acceleration: i

$$\Delta E_{max} = \left(\frac{M_b}{M_p}\right)^2 (\Lambda G)^{1/2} \left(\sqrt{\frac{G}{z^3 \times 1000[GV/cm]}}\right) \cdot 10^5 [TeV]^*$$

($M_b$ *and* $M_p$ are the mass of the beam particle and mass of the proton respectively, Λ is the de-channeling length per unit of energy, *G* is the accelerating gradient, and *z* is the charge of the beam particle)

- **0.3 TeV for electrons/positrons,**
- **$10^4$ TeV for muons,**
- **$10^6$ TeV for protons**

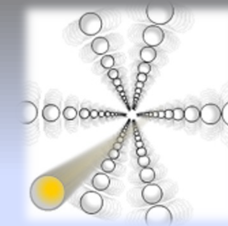
*P. Chen and R.J. Noble, in: Relativistic Channeling, eds. R.A. Carrigan, Jr and J.A. Ellison (Plenum, New York, 1987) p. 517.

# @ channeling for acceleration: ii

| | Dielectric based | Plasma based | Crystal channeling |
|---|---|---|---|
| Accelerating media | micro-structures | ionized plasma | solid crystals |
| Energy source: option 1<br>option 2 | optical laser<br>$e^-$ bunch | $e^-$ bunch<br>optical laser | x-ray laser<br>particle beam |
| Preferred particles | any stable | $e^-$, $\mu^-$ | $\mu^+$, $p^+$ (e+, e-) |
| Max acc gradient | 1-3 GV/m | 30-100 GV/m | 0.1-10 TV/m |
| c.m. energy in 10 km | 3-10 TeV | 3-50 TeV | $10^3$-$10^5$ TeV |
| # stages/10 km: option 1<br>option 2 | $10^5$ - $10^6$<br>$10^4$ – $10^5$ | ~100<br>$10^3$ - $10^4$ | ~ 1 |

- V. Shiltsev, Physics-Uspekhi (2012)
- F. Zimmermann, "The future of highest energy accelerators", CERN, Geneva, Switzerland

# @ Channeling … future …



- Beam Shaping (deflection, collimation, extraction)
- Crystal Channeling & Channeling related Radiation Phenomena
- Channeling in Combined Laser fields
- Channeling based phenomenology of known physical processes

(μ- & n-giudes, laser & plasma based acceleration)

- Channeling of Beams in Micro- & Nano-Structures

(compact accelerator, compact storage rings)

*channeling*

…

*… nice for "imagination" and useful in applications …*

# @ Channeling: papers - i

**Review papers related to this presentation (for general basic principles):**

- S.B. Dabagov, and A.V. Dik, Surface Channeling of Charged and Neutral Beams in Capillary Guides (invited review), *Quantum Beam Sci.* **6** (1) (**2022**) 8.
- S.B. Dabagov, and Yu.P. Gladkikh, Advanced Channeling Technologies for X-ray Applications (invited review), *Radiation Physics and Chemistry* 154 (2019) 3-16.
- S.B. Dabagov, Advanced Channeling Technologies in Plasma and Laser Fields (invited review), *European Physical Journal Web Conferences* 167 (2018) 01002.
- S.B. Dabagov, and N.K. Zhevago, "On radiation by relativistic electrons and positrons channeled in crystals" (invited review), *La Rivista del Nuovo Cimento* 31 (9) (2008) 491-529.
- S.B. Dabagov, "Channeling of Neutral Particles in Micro- and Nanocapillaries" (Reviews of Topical Problems), *Physics Uspekhi* 46 (10) (2003) 1053-1075.

# @ Channeling: papers - ii

**Proceedings of Channeling meetings (for complete activity list):**

- S.B. Dabagov, Ed., “Channeling 2023”, Proc. of the 9th International Conference "Charged and Neutral Particles Channeling Phenomena" (Riccione (Rimini), June 4-9, 2023), Nuclear Instruments and Methods in Physics Research A (2024).
- F. Zimmermann, and S.B. Dabagov, Ed., “Channeling 2018”, Proc. of the 8th International Conference "Charged and Neutral Particles Channeling Phenomena" (Ischia (Napoli), September 23-28, 2018), Physical Review: Accelerators and Beams (2019).
- S.B. Dabagov, Ed., “Channeling 2016”, Proc. of the 7th International Conference "Charged and Neutral Particles Channeling Phenomena" (Sirmione-Desenzano del Garda, September 25-30, 2016), Nuclear Instruments and Methods in Physics Research B402 (2017) 392 pp.
- S.B. Dabagov, Ed., “Channeling 2014”, Proc. of the 6th International Conference "Charged and Neutral Particles Channeling Phenomena" (Capri, October 5-10, 2014), Nuclear Instruments and Methods in Physics Research B355 (2015) 402 pp.
- S.B. Dabagov, Ed., “Channeling 2012”, Proc. of the 5th International Conference "Charged and Neutral Particles Channeling Phenomena" (Alghero, September 23-28, 2012), Nuclear Instruments and Methods in Physics Research B309 (2013) 280 pp.
- S.B. Dabagov, L. Palumbo, and V. Guidi, Eds., “Channeling 2010”, Proc. of the 4th International Conference "Charged and Neutral Particles Channeling Phenomena" (Ferrara, October 3-8, 2010), Nuovo Cimento C 34 (4) (2011) 560 pp.
- S.B. Dabagov, and L. Palumbo, Eds., Charged and Neutral Particles Channeling Phenomena - “Channeling 2008”, Proc. of the 51st Workshop of the INFN Eloisatron Project, World Scientific, (2010) 823 pp.
- S.B. Dabagov, Ed., “Channeling 2006”, Proc. of the International Conference on Charged and Neutral Particles Channeling Phenomena (Frascati, July 3-7, 2006), Proc. of SPIE 6634 (2007) .
- S.B. Dabagov, Ed., “Channeling 2004”, Proc. of the International Conference on Charged and Neutral Particles Channeling Phenomena (Frascati, November 2-6, 2004), Proc. of SPIE 5974 (2005) 506 pp.

# @ acknowledgements

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LPI & MEPHI & TPU & BSU (Russia), KhPTI (Ukraine)

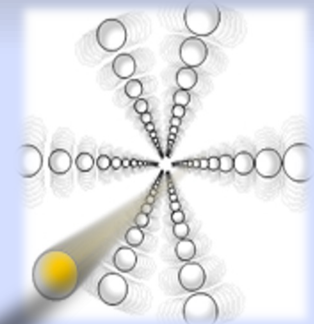
***Special acknowledgements for their exciting results on channeling physics!***

*Thank you for attention!*

…thanks for attention…

and

welcome to Channeling 2024



The 10th International Conference

CHARGED & NEUTRAL PARTICLES CHANNELING PHENOMENA

# CHANNELING 2024

8-13 September 2024

Riccione (Rimini), Italy

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**channeling2020@lists.lnf.infn.it**