Advanced Channeling Technologies to Guide Charged and Neutral Beams

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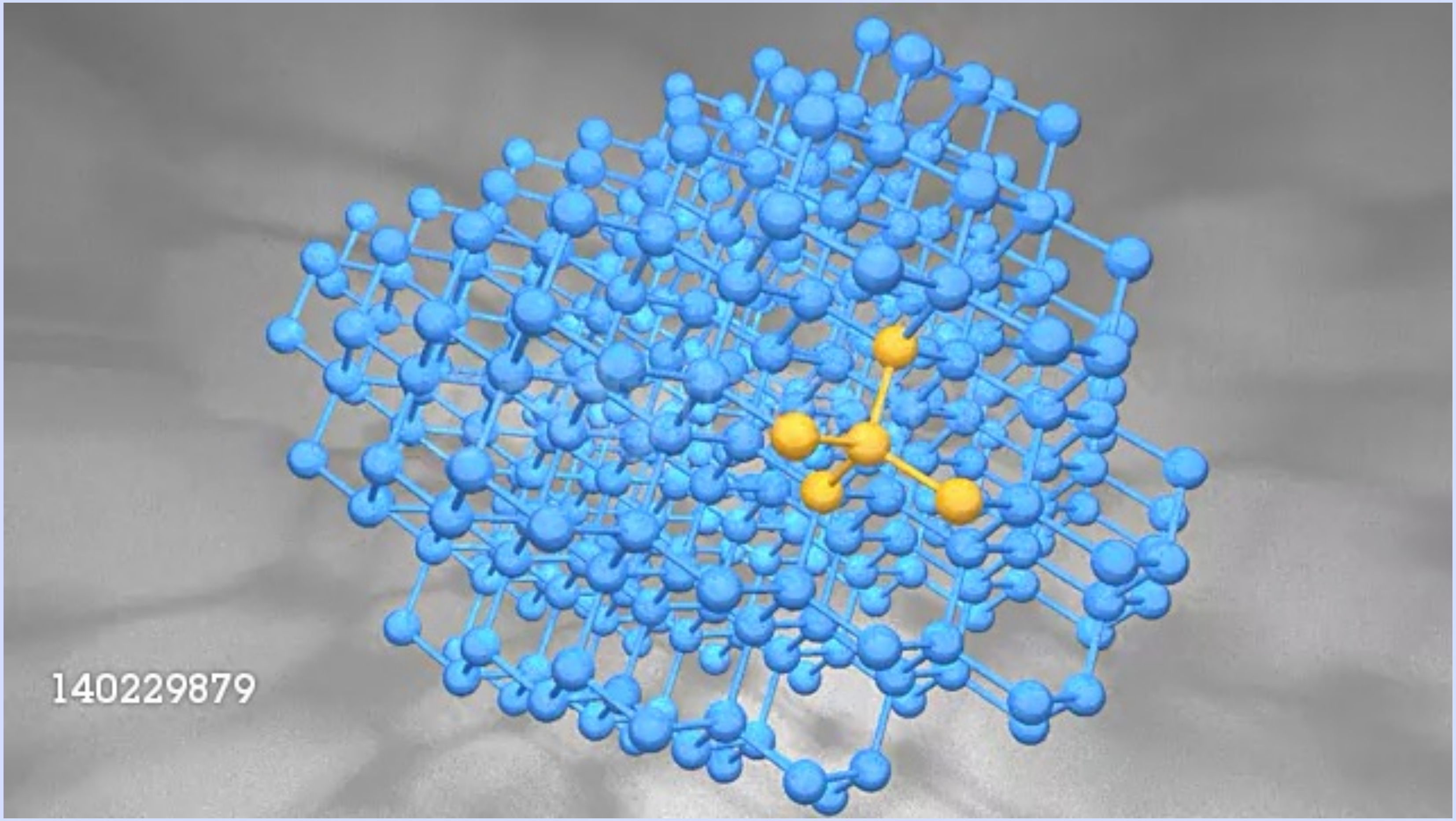
…thanking all my colleagues who contributed to this knowledge…

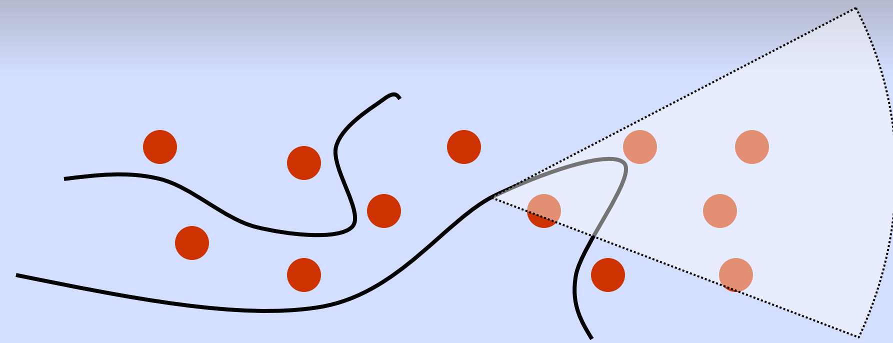
@ channeling…



…orientation dependent density… not only for crystals (!)

@ channeling of charged particles in crystals

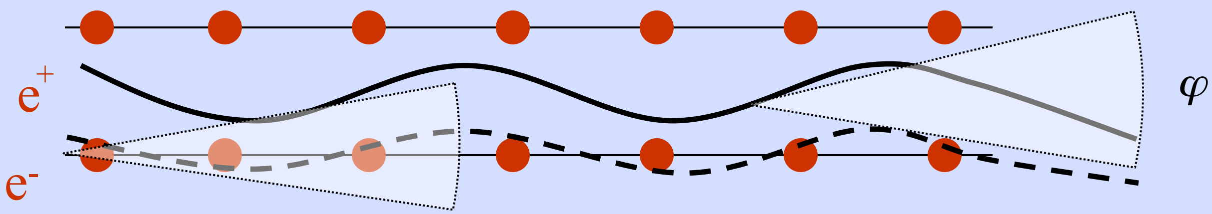
@ Amorphous:



@ Channeling: → **1** *...order...*

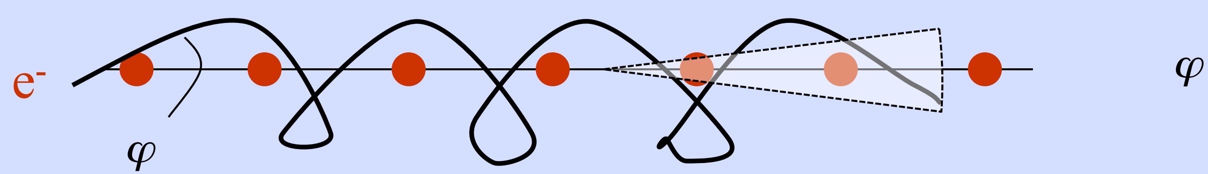
Atomic crystal plane – averaged/smeared continuous potential

planar



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

axial

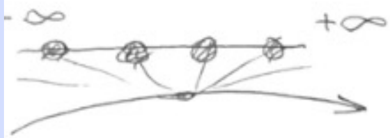


→ **2** *...small angle to main crystal directions...*

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

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

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



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

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

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

$e^2 \simeq 14.4\ eV \cdot \mathring{A}$

$$\int_{-\infty}^{+\infty} \frac{\varphi(r)}{r}\, dr \quad |\varphi(r/a)| \rightarrow \{\text{total}, \text{no}\} \rightarrow \{0 \div 1\}$$

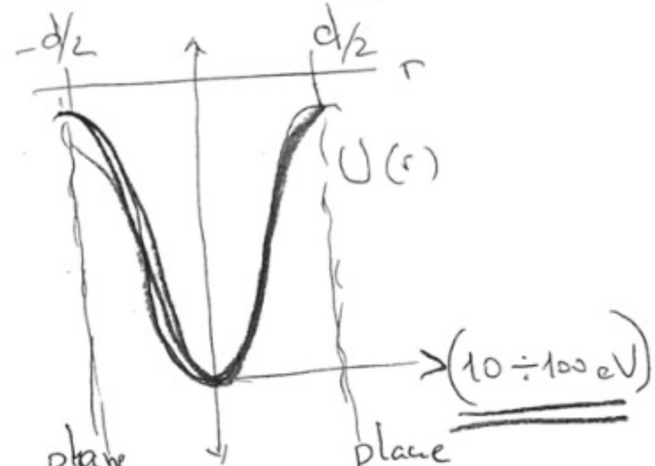
$\Downarrow$

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

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

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

crystal continuous potential



@ crystal fields for beams shaping/acceleration

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

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

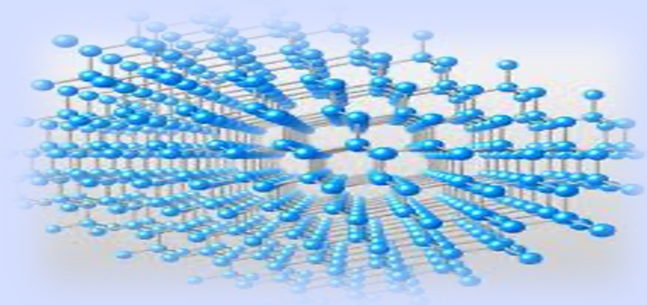
(!)

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

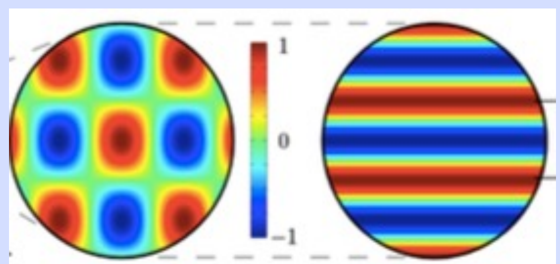
<u>Crystal fields</u> can provide much bigger gradients than modern <u>accelerator fields</u>

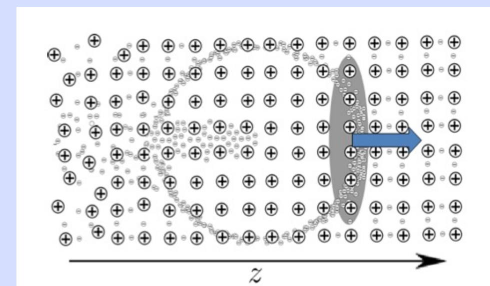
Channeling based applications for Charged & Neutral Beams: from Crystal to Capillary guides

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

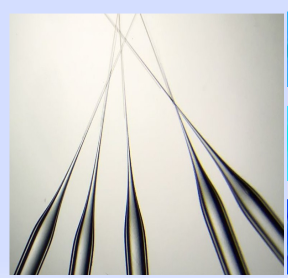


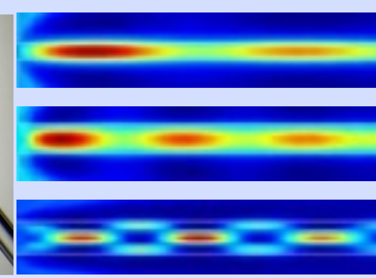
- **Laser & Plasma Channels**
  - Beam profiling for high current/luminosity;
  - Dynamics for wake field acceleration;

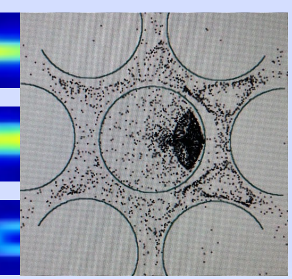




- **Capillary μ- and n-Channels**
  - beam redistribution;
  - Compact storage (?)

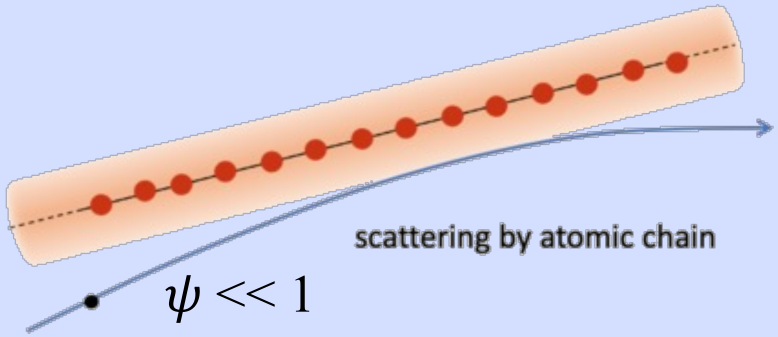


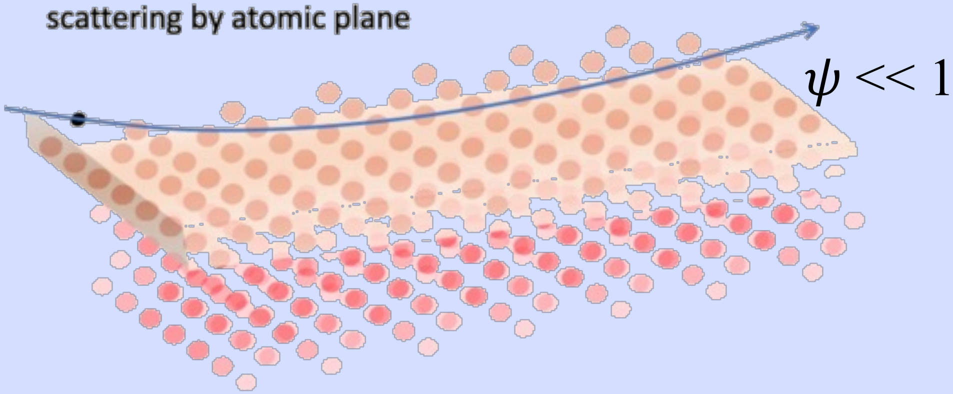




@ surface potential for reflection: first attempts - basics

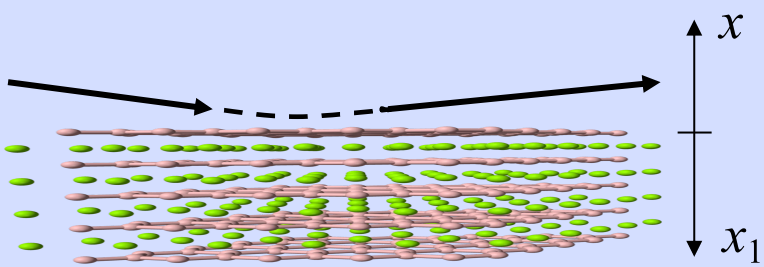
In the mid 80th of the last century Kumakhov & colleagues proposed to use smooth surfaces for effective deflection of charged particles... and further slowly bent surfaces for larger beam deflection





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

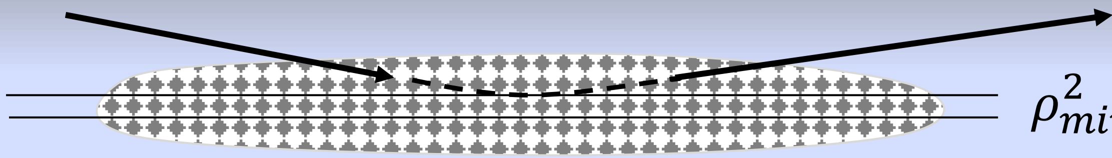


$$\mathbf{V}_{am}(x) = N_a \int_x^{\infty} V_a(x_1)dx_1$$

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

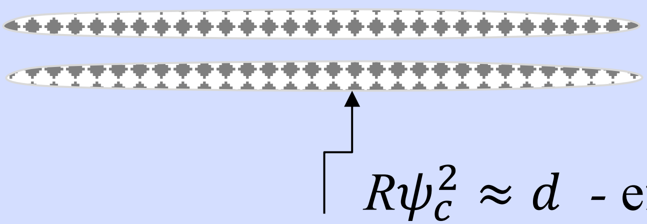


$\rho_{min}^2 \approx (\rho^2 + a^2)$ mirror reflection

Amorphous surface potential
//Molier approximation//

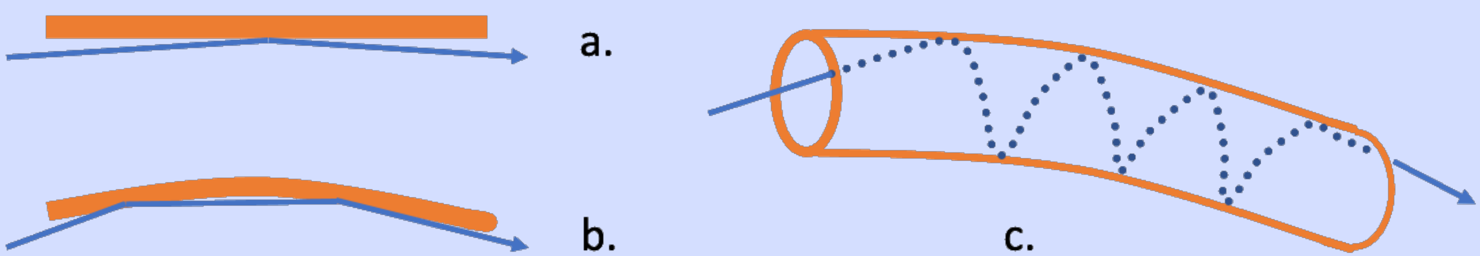
$$\mathbf{V}_{am}(x) = 2\pi N_a Z_p Z_a e^2 a_{TF}^2 \sum_{i=1}^{3} (\alpha_i/\beta_i^2) \exp(-\beta_i x/a_{TF})$$

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



d channeling between 2 planes over a long distance

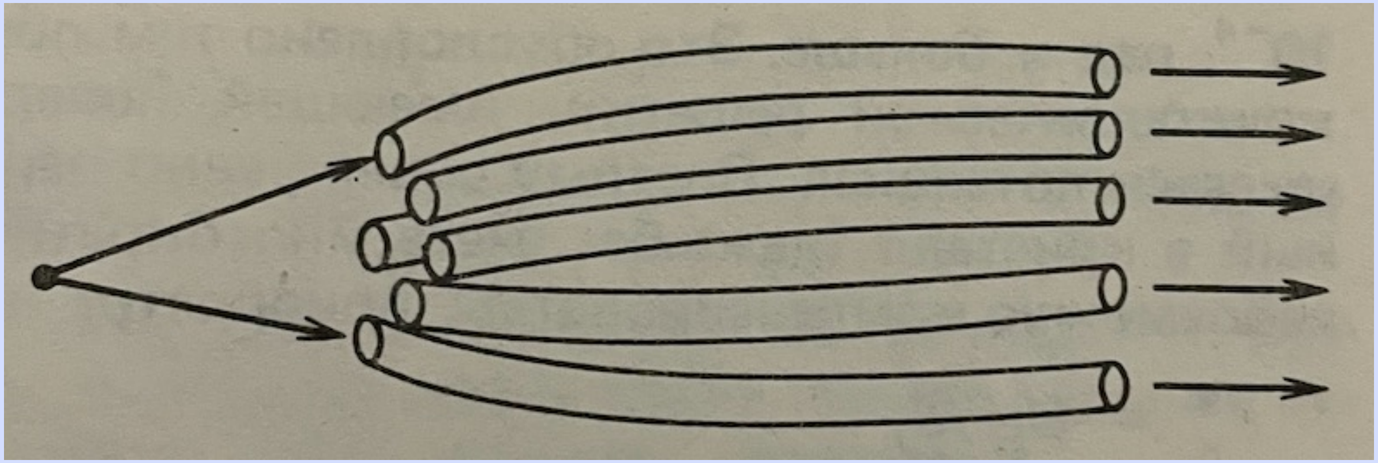
$R\psi_c^2 \approx d$ - effective bending by large angles



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

c: effective large angle 2d-bending

Capillary Optics*…capillaries as guides for beams…*



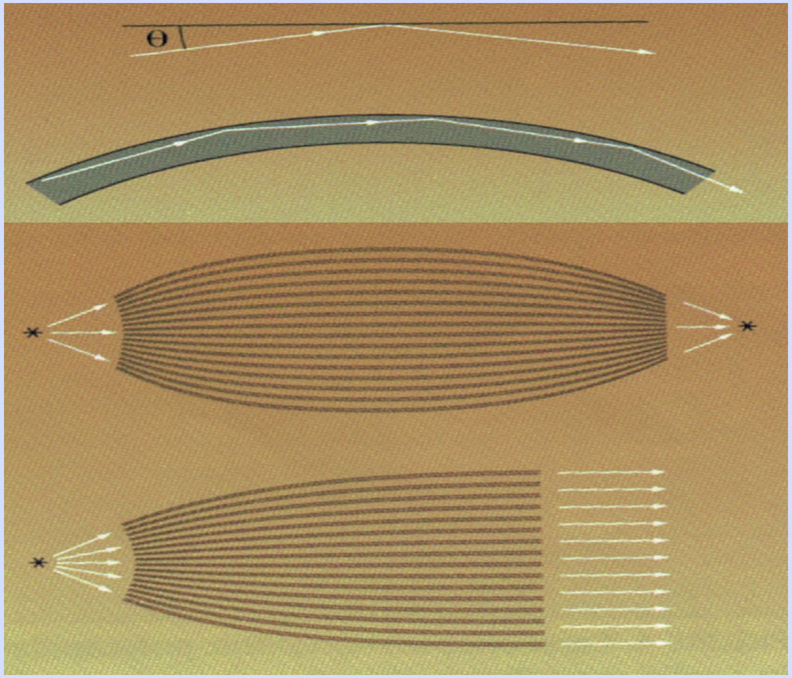
Capillary based Ion Optics

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 lenses for soft X-ray focusing

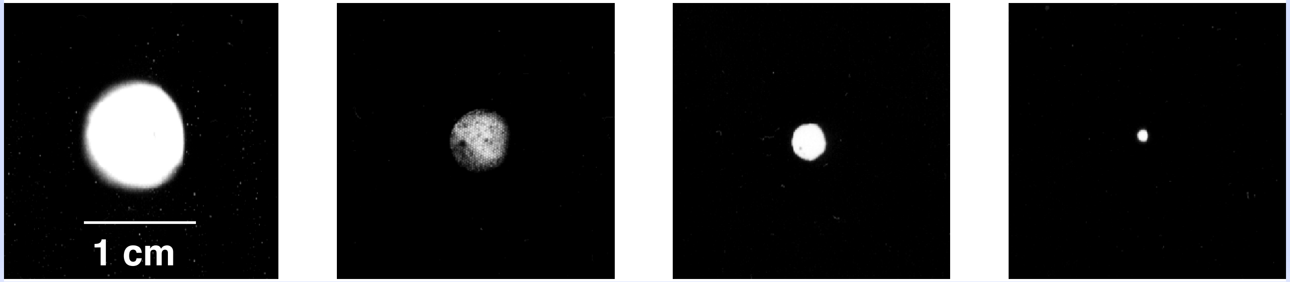
Capillary guides reveals much advanced technological development leaving frozen capillary based ion optics practically for 10-15 years



~10 cm

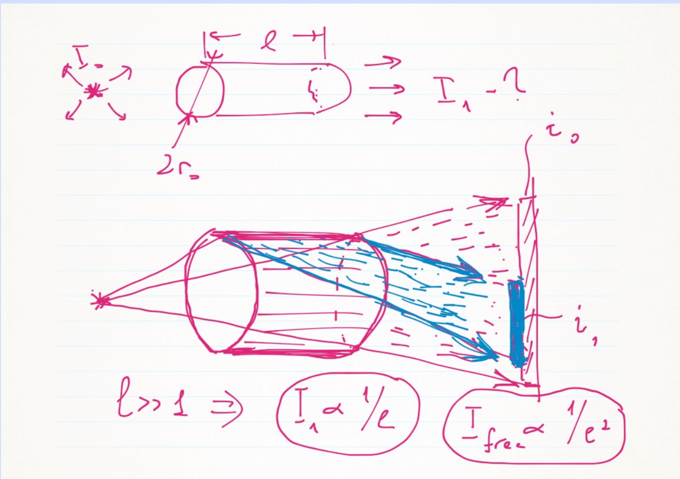
Gain ≈ 30 for 2 mm diaphragm

Focal distance ~ 10 cm

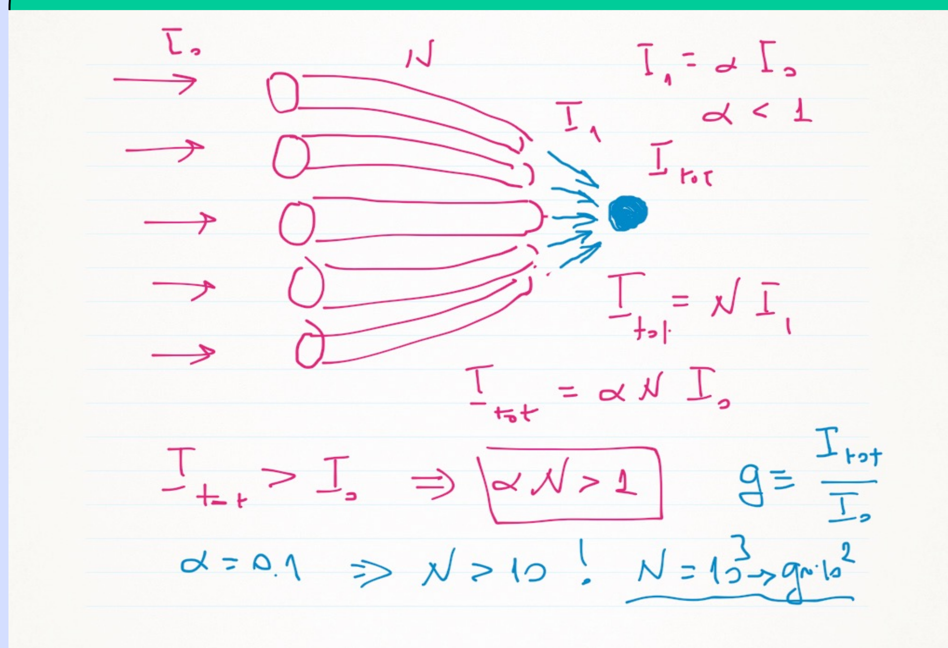


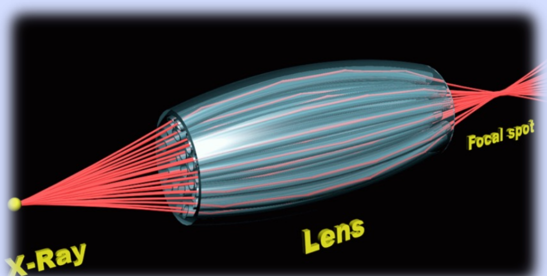
Gain ≥ 100
for 1 mm diaphragm

Polycapillary optics *…first estimations…*



Kumakhov’s task (Minsk school, 1984):
a night work for the feasibility of mono/multichannel optics

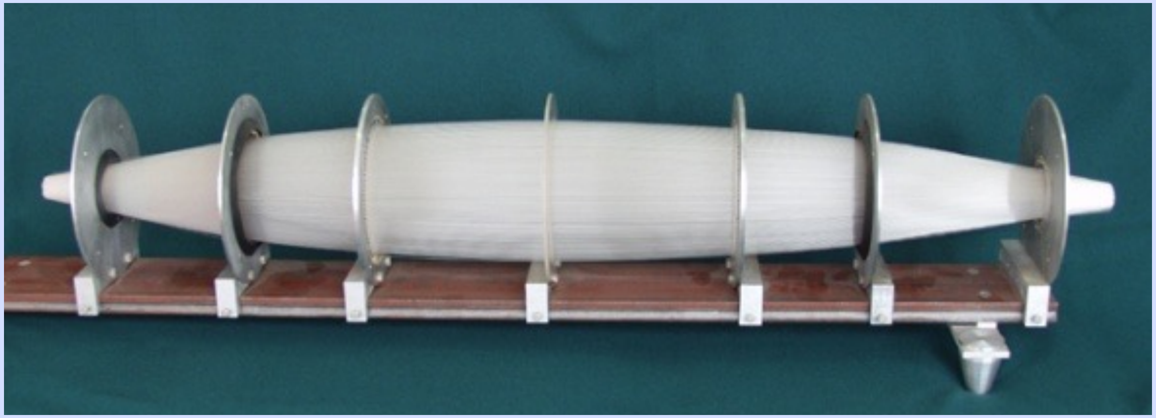




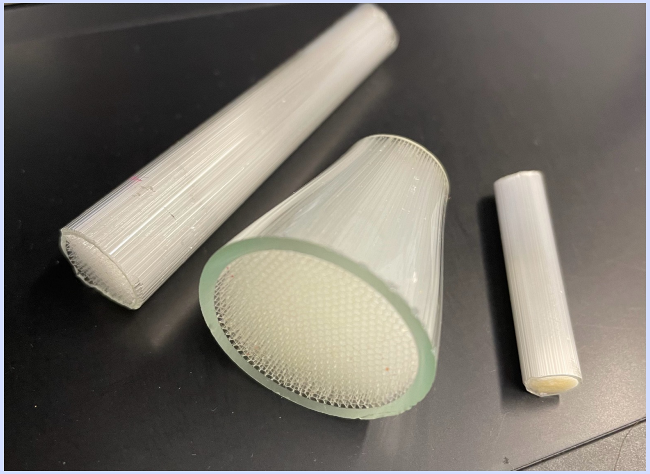
… first virtual image …

Polycapillary optics *…from discussions in 1984 to first prototype in 1986…*

First X-ray polycapillary optics
/manually assembled/
~ 1 m length
~ 30 cm in diameter 10 000
monocapillaries
~ 1 year fabrication



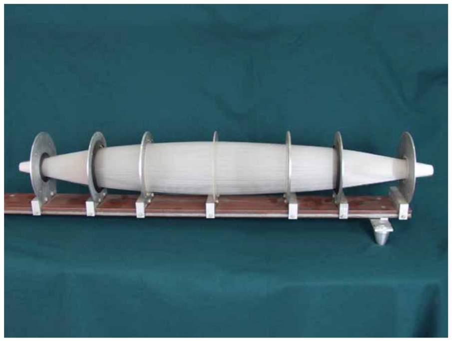
first prototype (handmade) of "Kumakhov lens" ←→ "Kumakhov optics"



first polycapillary optical elements (machine drawn)

Polycapillary optics *…evolution of the technology…*

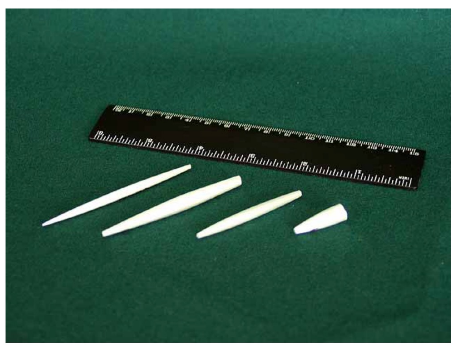
1st - assembled lens made of single capillaries



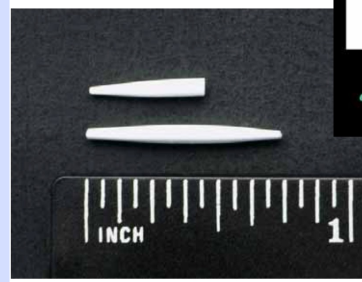
2nd - monolithic lens made of single capillaries

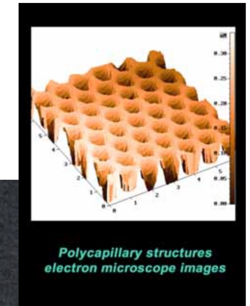
3rd - assembled lens made of Poly capillaries

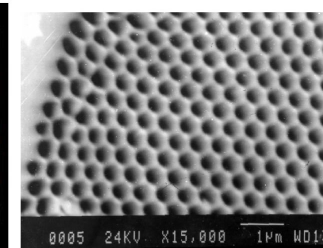
4th - monolithic lens made of Poly capillaries

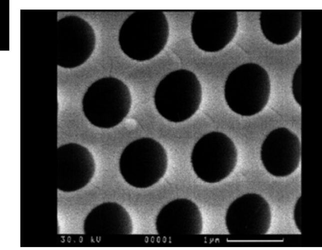


5th - monolithic integral micro lens







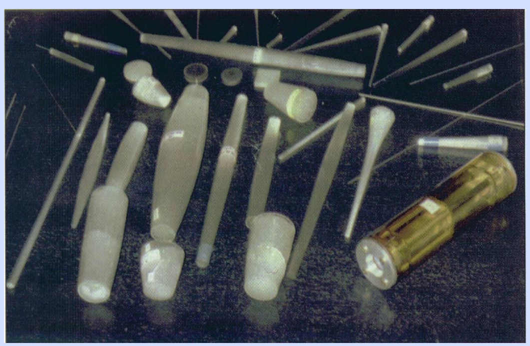


Sub-Micron Capillary Technology

Technology: Drawing machines

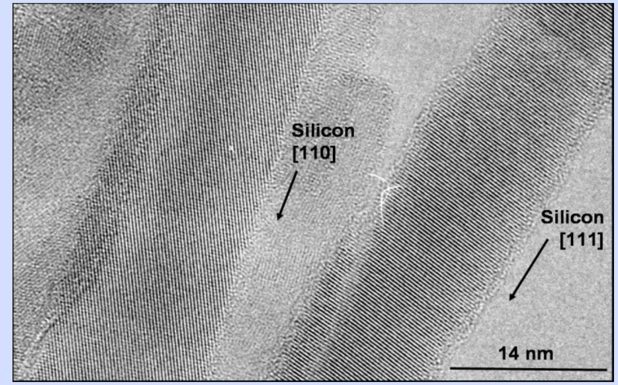
Polycapillary optics *…from micro- down to nano-channels…*

Micro-
capillaries

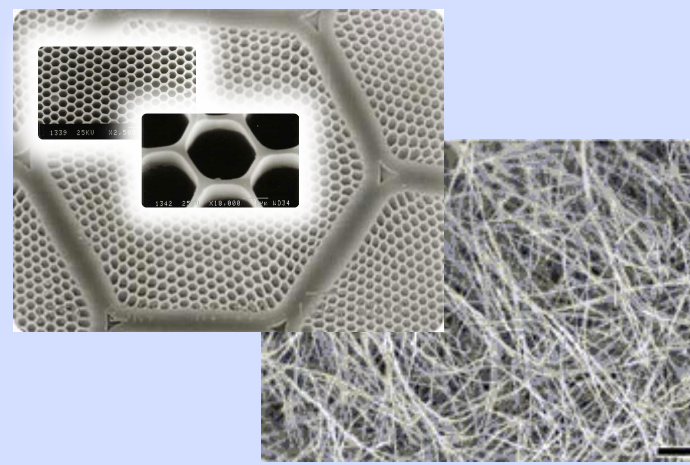


Micro → X-rays

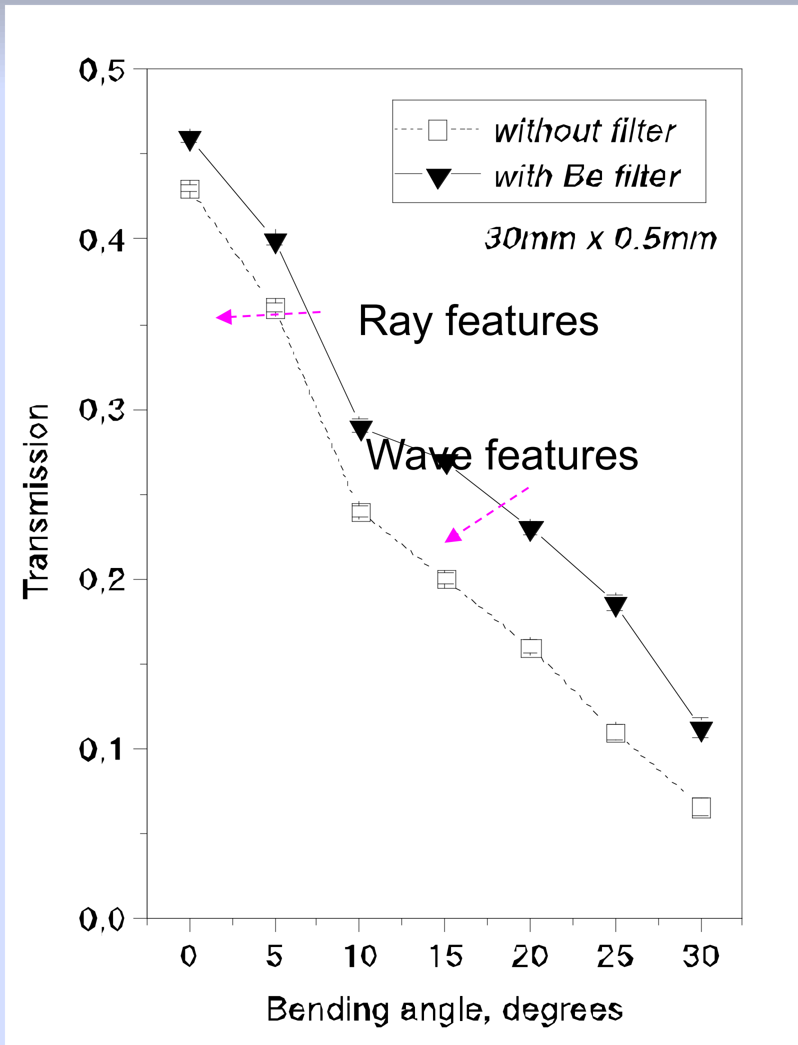
Nano → γ-rays (?)



Nanotubes &
Nanochannels

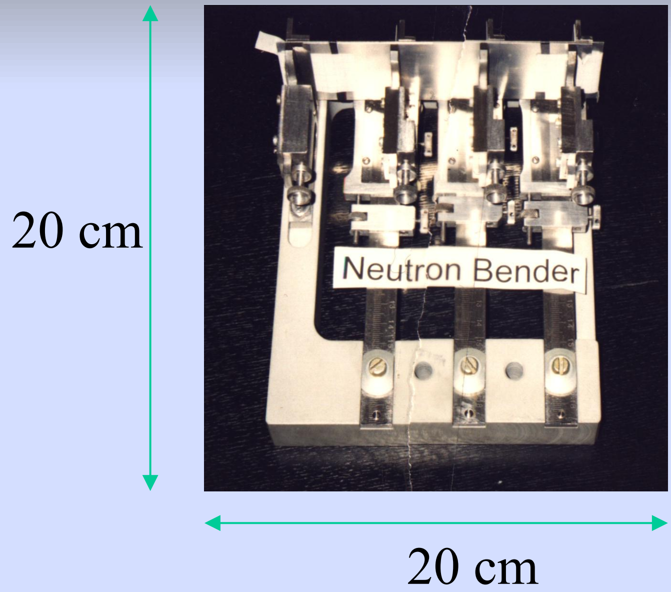


@ neutron beam bending



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

<d> ~ 10 μm   <L> ~ 16 cm.



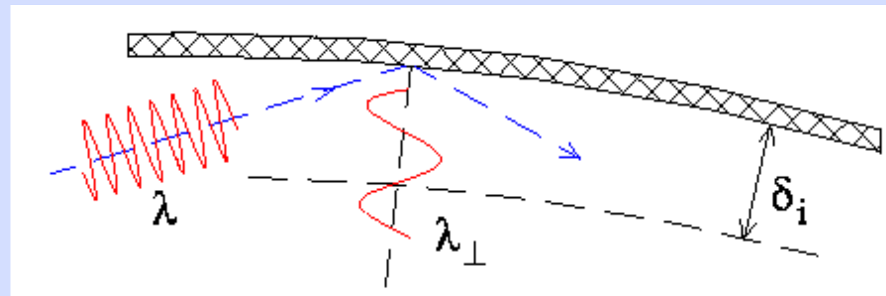
First capillary (poly) based thermal neutron bender applied at Hann-Meitner Inst (Berlin) in 1995.

@ 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

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

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

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

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

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

Upper limit of the curvature radius

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

$$\lambda \sim 1\ \text{Å}$$

@ quantum basics for x ray channeling

$\theta << 1$

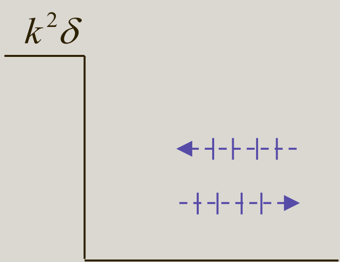
$k_\perp \approx k\theta$

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

Wave equation:

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

plane surface

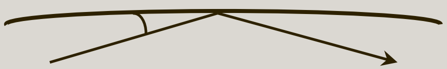


$$k^2\left(\delta(\vec{r}_\perp) - \theta^2\right) =$$

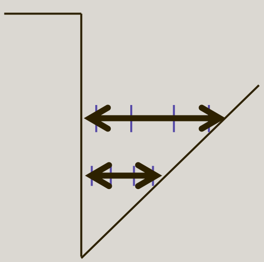
$$= \begin{cases} -k^2\theta^2, & r_\perp < r_1 \\ k^2(\delta_0 - \theta^2), & r_\perp \geq r_1 \end{cases}$$

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

TER



curved surface

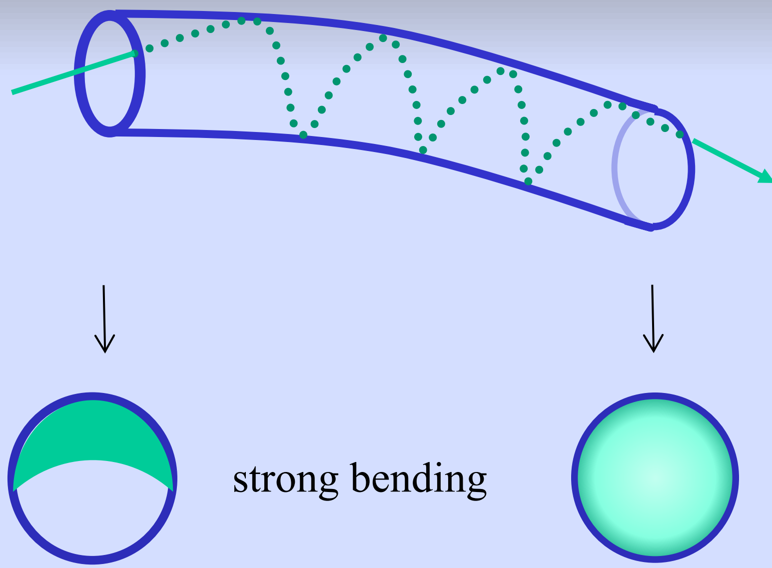


$2\dfrac{-k^2 r_\perp}{r_{curv}}$ *potential energy due to angular momentum* $k r_{curv}\varphi$

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

CHANNELING

@ circular μ-guide



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

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

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 $r_1 \in (r_0, R)$.

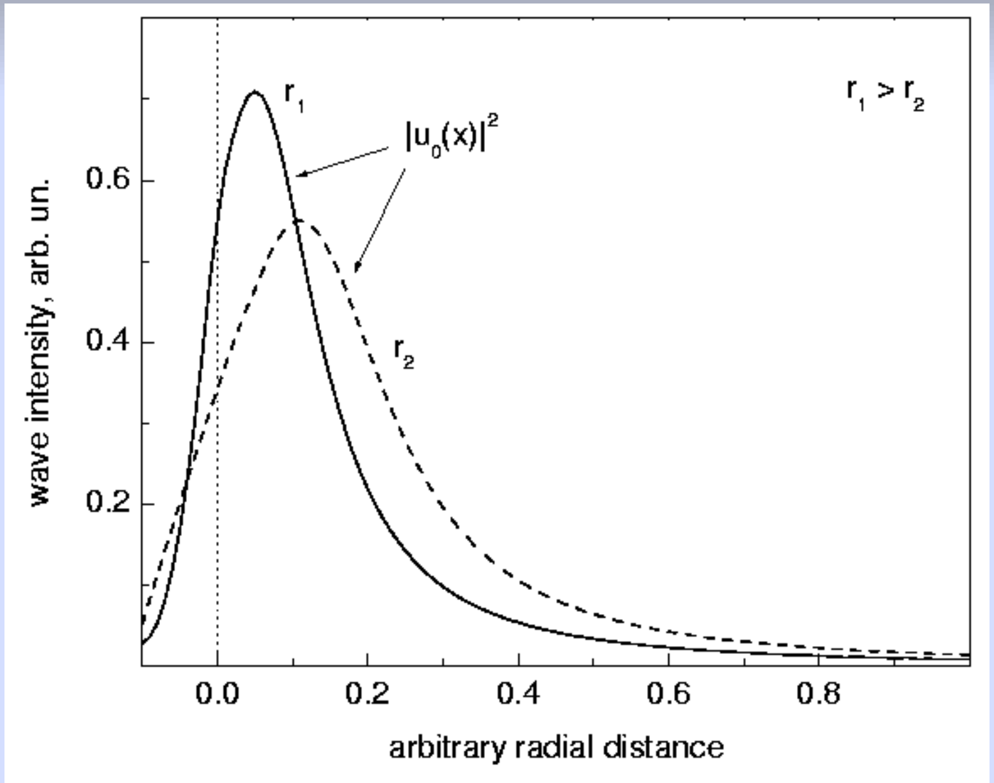
$$2\pi^2 \overline{u}_0^3 \simeq \lambda^2 r_1 \longleftarrow \text{single mode propagation}$$

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)

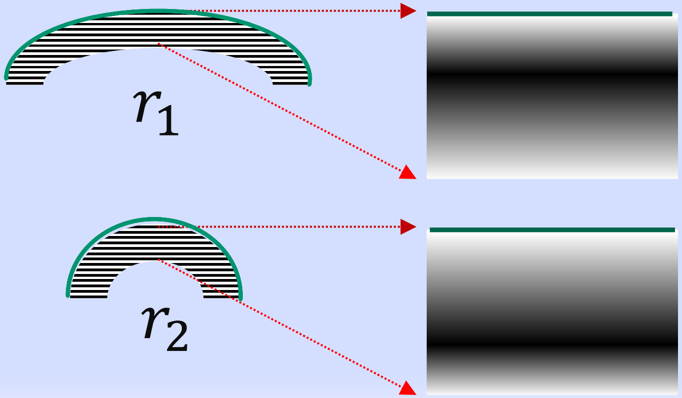
@ smooth channel surface: radial wave distributions



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

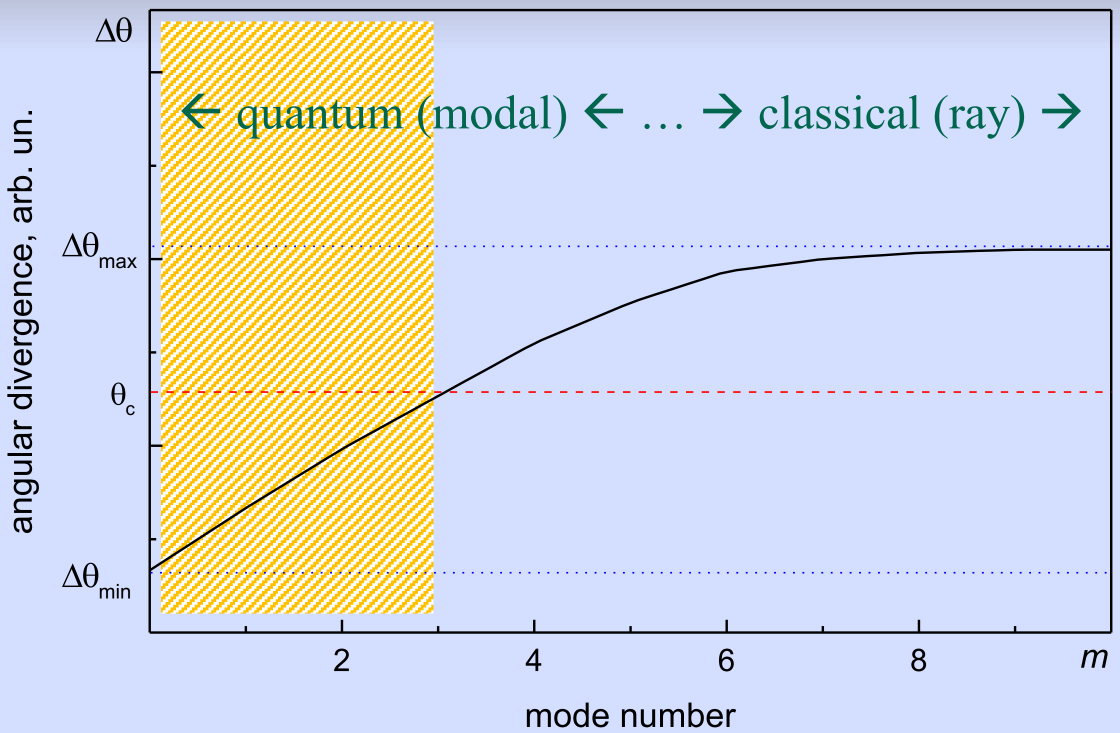
$$< u_0 > \simeq \left(\frac{\lambda^2 r_1}{2\pi^2}\right)^{1/3}$$

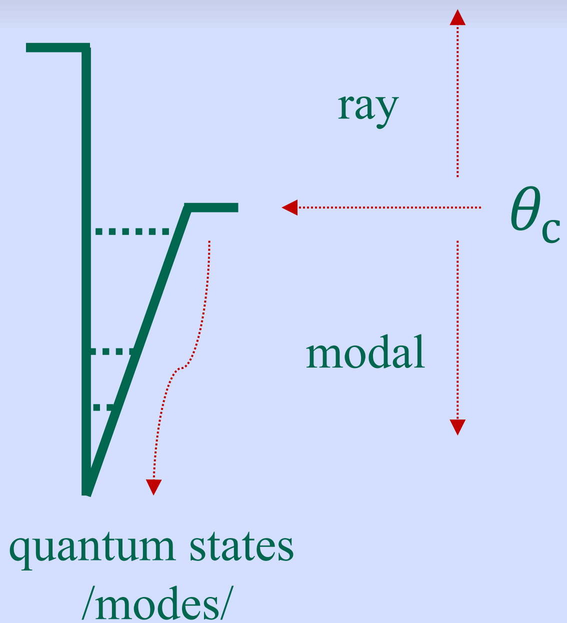
The typical radial size of the main grazing mode
m=0 may essentially overcome the wavelength



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)

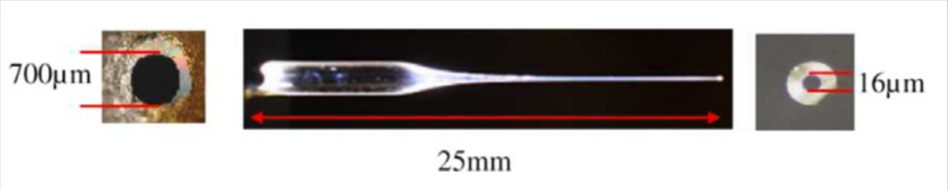
Since the first observations of the passage of ions through dielectric capillaries [*Stolterfoht, N., Bremer, J.H., Hoffmann, V., Hellhammer, R., Fink, D., Petrov, A., et al. Transmission of 3 keV Ne7+ ions through nanocapillaries etched in polymer foils: Evidence for capillary guiding. Phys Rev Lett 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).

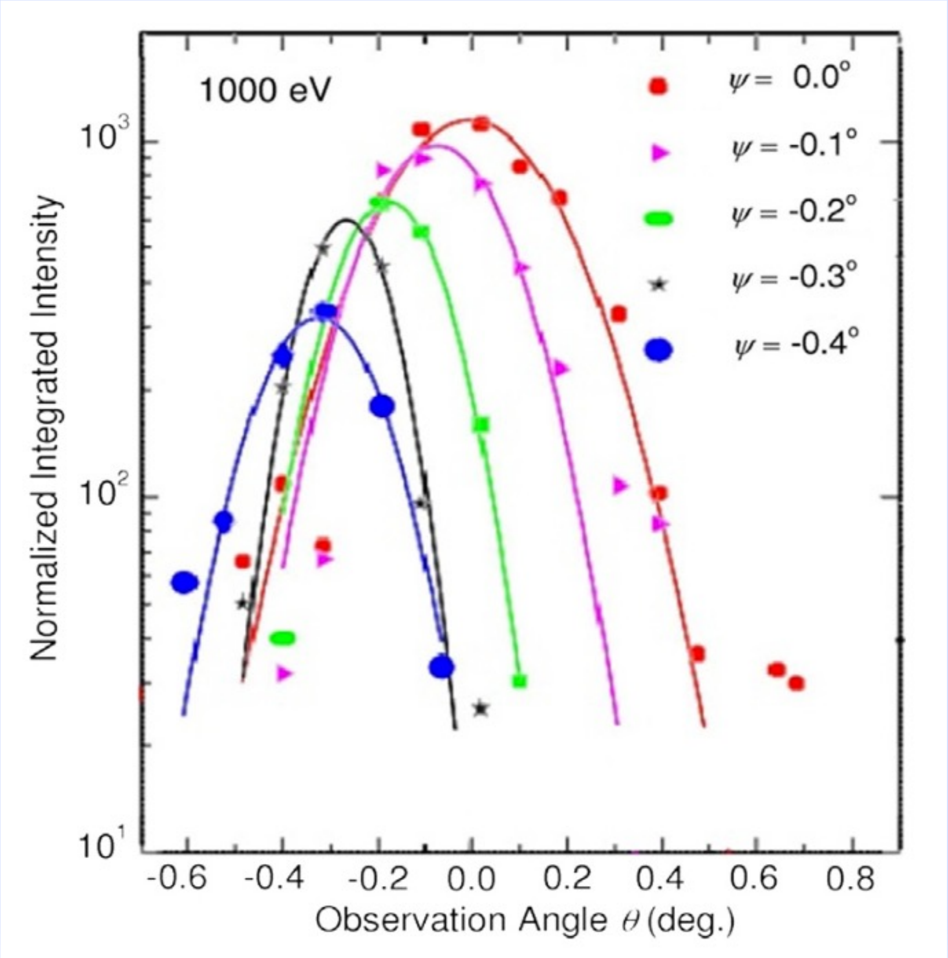
Known theoretical studies mainly aim at simulating the motion of charged particle beams inside capillary insulators using the Monte Carlo method [*Schiessl, K., Palfinger, W., Lemell, C., Burgd¨orfer, J.. Simulation of guiding of highly charged projectiles through insulating nanocapillaries. Nucl Instr 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.



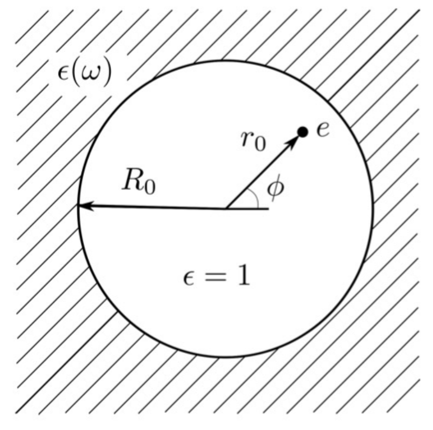
Significantly larger tilt angles than the aspect angle -> *the electrons must have interacted at least once with the capillary surface*

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 $\varepsilon(\omega)$, with a particle of the charge e moving inside the cavity. For the cavity we choose $\varepsilon = 1$.

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

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

From the condition of continuity of the electric and magnetic fields components tangential to the interface, we derive the dispersion law $k(\omega)$ with $x = kc/\omega$ and $\alpha = R_0\omega/c$

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

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

$\alpha \ll 1$ -- only at $\varepsilon(\omega) = -1$,
$\alpha \gg 1$ -- the solution in the form of a series expansion in powers of a small parameter $(1/\alpha)$

@ 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

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

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.

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

@ 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

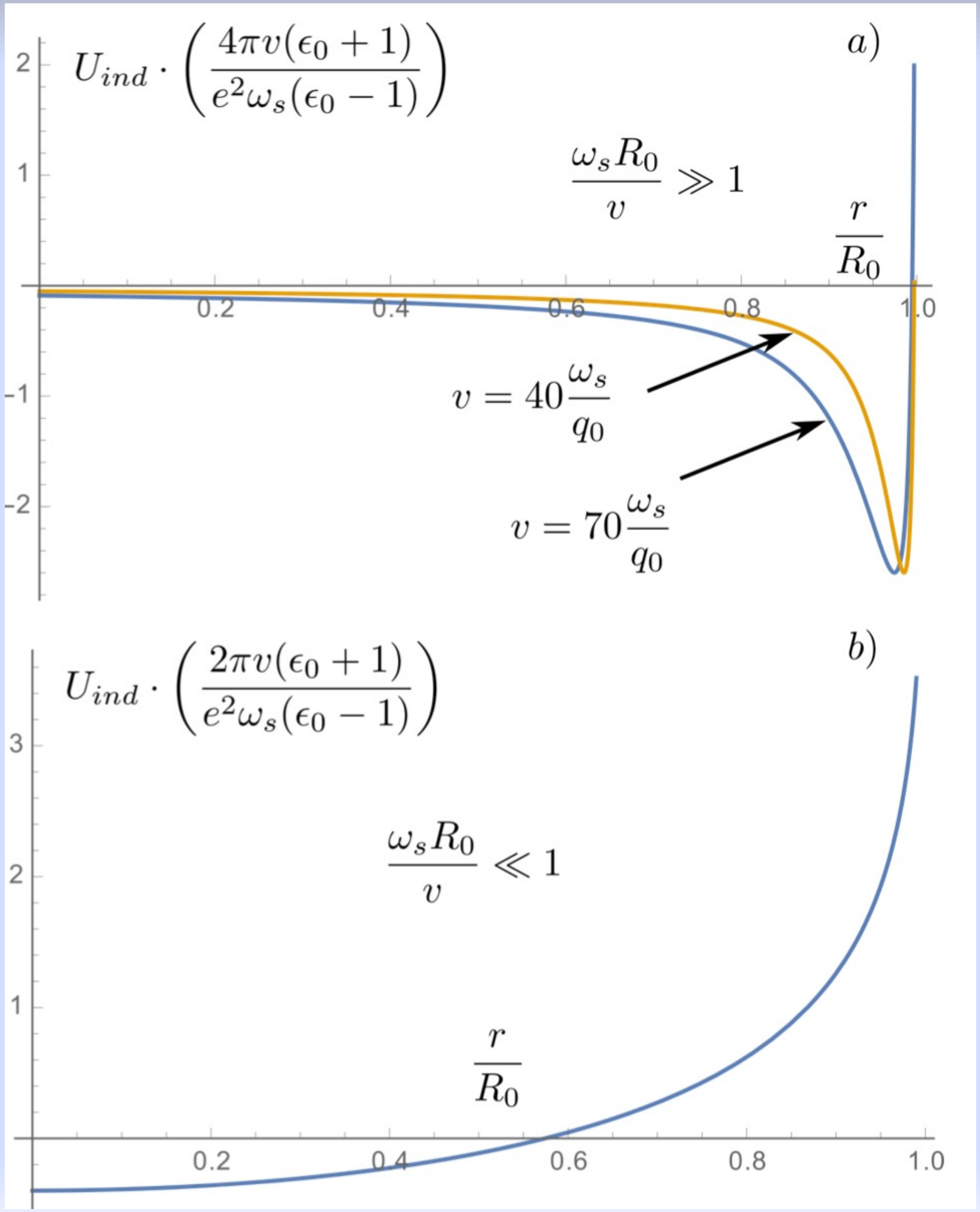
@ the 1st - a continuous potential via known technique in channeling physics and does not result in any unexpected behaviours;

@ 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



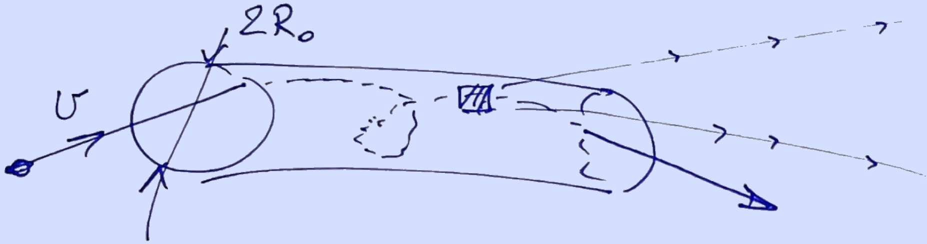
Dimensionless induced potential versus the distance from the cavity axis.

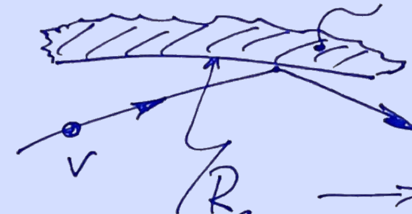
a). The graph at the condition $\omega_s R_0/v \gg 1$ shows two curves corresponding different values of longitudinal velocity. As seen, at the particle velocity increase the potential shape does not change, and the curve minimum tends to the cavity center.

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





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

R_{bend}: $\uparrow$ max $\downarrow$ ω_{min}

R_0: $\uparrow$ min $\downarrow$ $\omega_{max} \equiv \omega_0$

$v \oplus R_{curv} \to \omega$ for particle

particle $\to$ some kind of cyclotron frequency

$$\left(v/R\right) \equiv \left(v/R_{curv}\right) \xrightarrow[max]{} \frac{v}{R_0} \Rightarrow \omega_0 \to \omega_{max}$$

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

$\begin{cases} \omega_s/\omega \ll 1 \to \text{for analysis } \omega_{max} \to \frac{v}{R_0} \to \omega_0 \\ \omega_s/\omega \gg 1 \end{cases}$

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

b: $(\omega_s/\omega_0) \gg 1$ $\to$ surface plasmons more energetic $\Rightarrow$ potential averaging // induced potential with minimum $\Longleftrightarrow$ surface channeling

@ Resume: charged particles

For the first time shown that at the limit

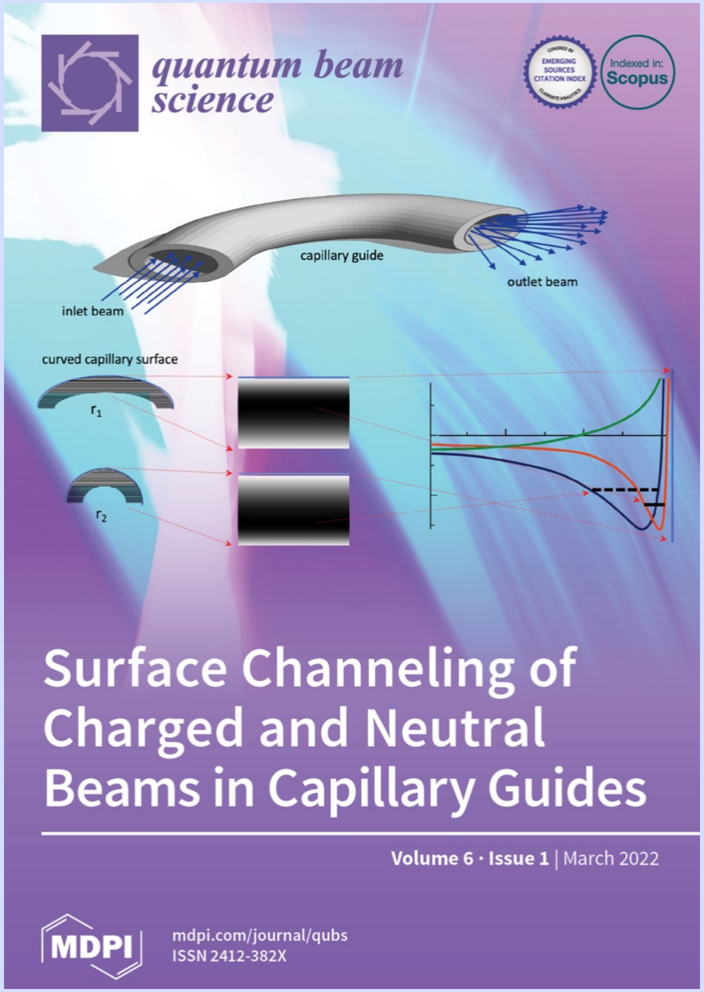
- $\omega_s R_0/v \ll 1$ the induced potential of interaction of a charged particle with the cavity surface acts as a scattering potential (forming a reflecting barrier);

- $\omega_s R_0/v \gg 1$ 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.

@ Resume

Channeling formalism, i.e. surface channeling one, allows describing the fine features of beams/radiations propagation along curved surfaces. It is also rather efficient tool for the definition of main characteristics for capillary guiding



quantum beam science

MDPI

Review

Surface Channeling of Charged and Neutral Beams in Capillary Guides

Sultan Dabagov [1,2,3,*] and Alexey Dik [3]

[1] INFN Laboratori Nazionali di Frascati, Via e. Fermi 54, I-00044 Frascati, RM, Italy
[2] National Research Nuclear University MEPhI, Kashirskoe Sh. 31, 115409 Moscow, Russia
[3] P.N. Lebedev Physical Institute, Russian Academy of Sciences (RAS), Leninsky Pr. 53, 119991 Moscow, Russia; dik.alexey@gmail.com
* Correspondence: sultan.dabagov@lnf.infn.it

Abstract: In this review work, the passage of charged and neutral beams through dielectric capillary guides is described from a uniform point of view of beams channeling in capillaries. The motion of beams into the hollow channels formed by the inner walls of capillaries is mainly determined by multiple small-angle scattering (reflection) and can be described in the approximation of surface channeling. It is shown that the surface interaction potential in the case of micro- and nano-capillaries is actually conditioned by the curvature of the reflecting surface. After presenting the analysis of previously performed studies on X-rays propagation into capillaries, which is valid for thermal neutrons, too, the surface channeling formalism is also developed for charged particle beams, in particular, moving in curved cylindrical capillaries. Alternative theories explaining experimental results on the beams passage through capillaries are based on simple thermodynamic estimates, on various diffusion models, and on the results of direct numerical simulations as well. Our work is the first attempt to explain the effective guiding of a charged beam by a capillary from the general standpoint of quantum mechanics, which made it possible to analytically explore the interaction potential for surface channeling. It is established that, depending on the characteristics of a projectile and a dielectric forming the channel, the interaction potential can be either repulsive or attractive; the limiting values of the potential function for the corresponding cases are determined. It has been demonstrated that the surface channeling behaviour can help in explaining the efficient capillary guiding for radiations and beams.

Keywords: capillary guiding; surface channeling; capillary optics

Citation: Dabagov, S.; Dik, A. Surface Channeling of Charged and Neutral Beams in Capillary Guides. *Quantum Beam Sci.* **2022**, *6*, 8. https://doi.org/10.3390/qubs6010008

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. https://doi.org/ 10.3390/qubs6010008

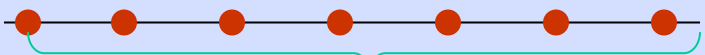
…thanks for attention…

…additional…

Crystal Channeling *… continuous model…*

$$V(r) = \frac{Z_1 Z_2 e^2}{r}\varphi(r/a)$$ screening function of Thomas-Fermi type

$$a = .8853 a_0 \left(Z_1^{1/2} + Z_2^{1/2}\right)^{-2/3}$$ screening length



fast motion -- averaging

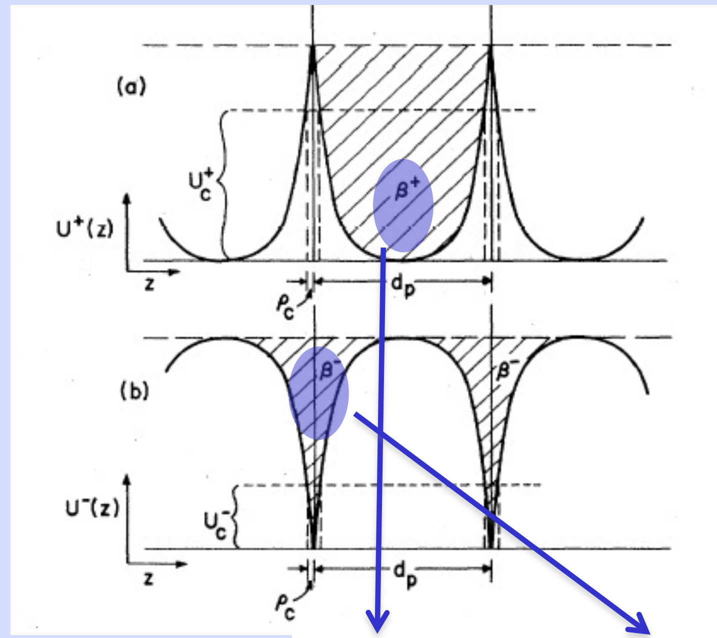
Lindhard: Continuum model – continuum atomic plane/axis potential

$$V_{RS}(\rho) = \frac{1}{d}\int_{-\infty}^{+\infty} V\left(\sqrt{\rho^2 + x^2}\right)dx$$

$$\varphi(r/a): \quad \sum_{i=1}^{3} \alpha_i \exp(-\beta_i r/a)$$ Molier' s potential

$$1 - \left[1 + \frac{Ca}{r^2}\right]^{-1/2} \qquad C^2 \approx 3$$ Lindhard potential

…… Firsov, Doyle-Turner, etc.



$$\left(\frac{\partial U}{\partial x}\right)_{plane} \ll \left(\frac{\partial U}{\partial x}\right)_{axis}$$

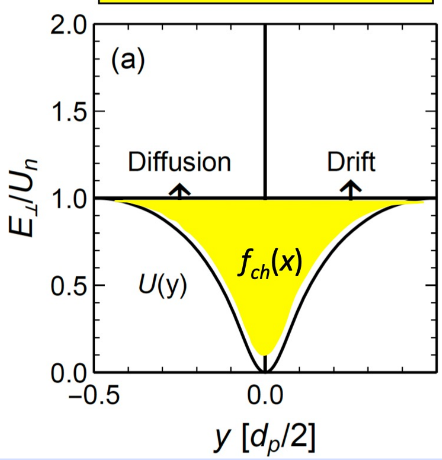
Fokker-Planck equations *…strong beam redistribution in transverse space up to equilibrium condition…*

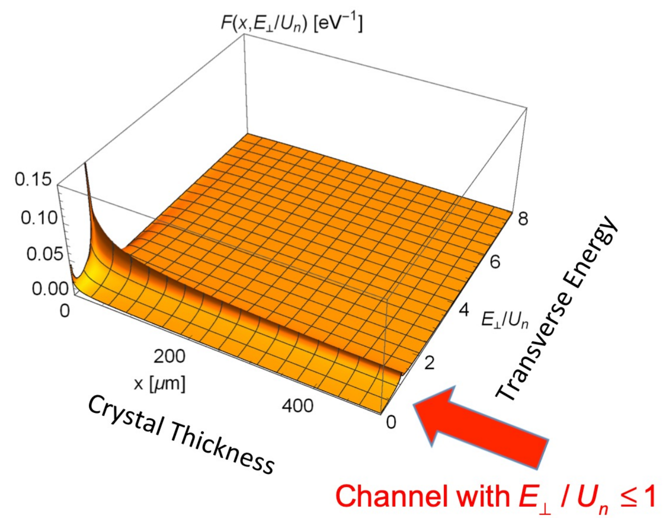
$$\frac{\partial F(x,E_\perp)}{\partial x} + \frac{\partial J(x,E_\perp)}{\partial E_\perp} = 0$$

continuity equation with density F and current J

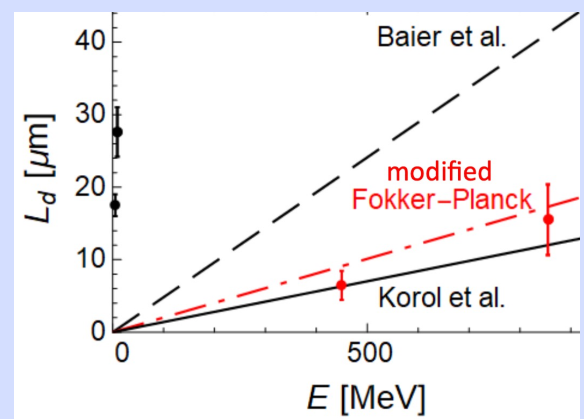
$$J(x,E_\perp) = -\frac{\partial}{\partial E_\perp}\left[D_e^{(2)}(E_\perp)\,F(x,E_\perp)\right] + D_e^{(1)}(E_\perp)\,F(x,E_\perp) = J_{diff}(x,E_\perp) + J_{drift}(x,E_\perp)$$

$$\boxed{f_{ch}(x) = \int_{E_\perp=0}^{U_n} F(x,E_\perp)\,dE_\perp}$$



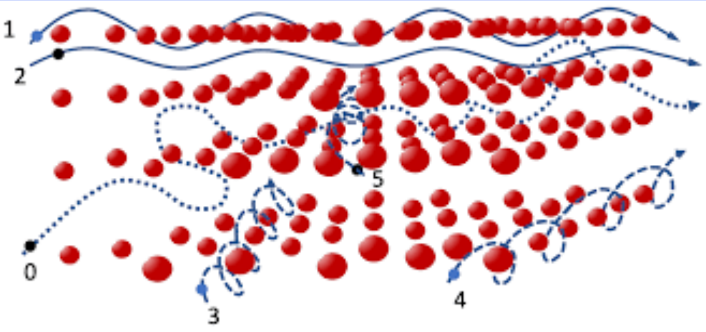


- *Potential 'smearing' – averaging bring us by default to statistical equilibrium that allows main features to be described within simplified approximation*
- *Recent studies proved a better analytical approximation (MAMI exp.)*

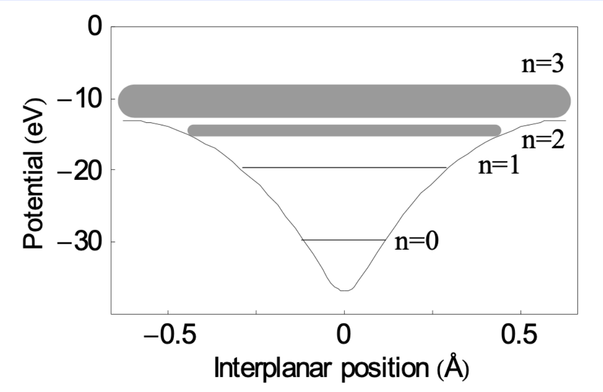


// Backe at Channeling 2018//

Channeling Radiation *...prediction...*



- Various types of channeling in aligned crystals (curves 1-5) vs amorphous orientation (curve 0) – periodicity in trajectory → *undulation... extremely compact undulator !*



- Very simple dynamics $\frac{d}{dt}\frac{m_e v_x}{\sqrt{1-(v_x^2+v_z^2)/c^2}} = -2U_0 x$ $\left\{ \begin{array}{l} x(t) = x_m \cos \Omega t \\ \Omega^2 = \Omega_0^2 \sqrt{1-\beta^2} \end{array} \right.$

- Extremely powerful radiator $I = \frac{2}{3}\frac{e^2 c}{R^2}\gamma^4$

$$\bar{I} = \frac{e^2 x_m^2 \Omega^4 \gamma^4}{3c^3} = \frac{e^2 x_m^2 \Omega_0^4 \gamma^2}{3c^3} \quad \leftrightarrow \quad dE_r/dx = I/c$$

$I \sim \Omega_0^4 \sim (dU/dx)^2$ *Radiation power up to 10 4 (eV/Å)*

From optical frequencies … infrare

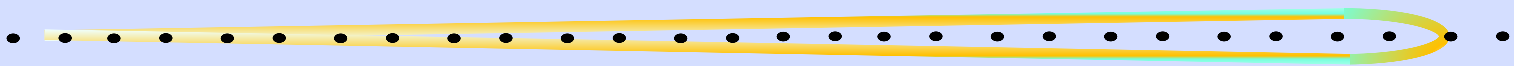
$$\omega = \frac{\Omega}{1-\beta \cos\theta}$$

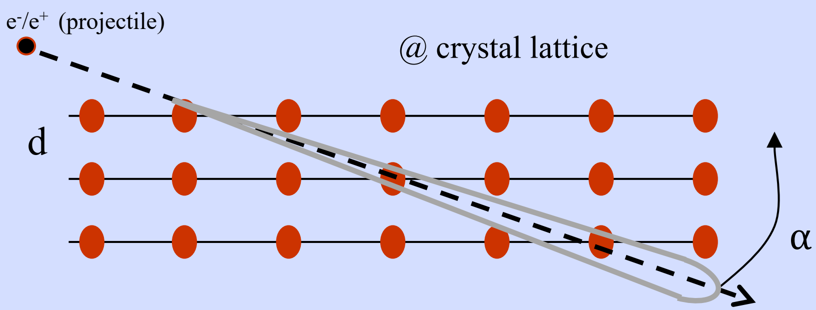
$$\omega_m = (1+\beta)\gamma^2 \Omega \simeq 2\gamma^{3/2}\Omega_0$$

to X and γ frequencies

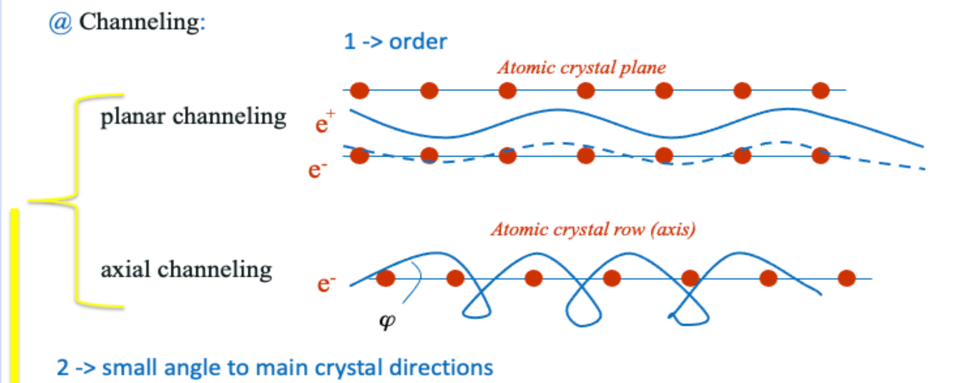
Kumakhov was the first who evaluated the radiation at channeling CORRECTLY taking into account relativistic factor (Doppler effect)

Bremsstrahlung & Coherent Bremsstrahlung & Channeling Radiation



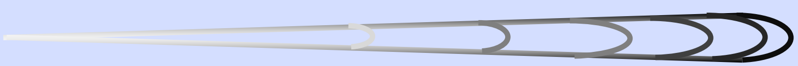


$\alpha \to 0$ → channeling orientation



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

$l_{coh} \propto \gamma^2 \lambda$ radiation coherence length for denser orientation



B:	CB:	CR:
	NZe	$N \leftrightarrow \quad l_{coh} \propto \gamma^2/\omega \quad N_{eff}$
$\propto NZ^2$	$\propto (NZ)^2$	$\propto (N_{eff}Z)^2$

Crystal based radiators

$$\omega = \frac{\omega_{fi}}{1 - \beta_{\|} \cos\theta}$$ - from optical to γ frequencies

$$\left(\frac{dI}{d\omega}\right)_{CR} \propto \omega \left[1 - 2\left(\frac{\omega}{\omega_m}\right) + 2\left(\frac{\omega}{\omega_m}\right)^2\right], \quad \omega \leq \omega_m \simeq 2\gamma^2\omega_{fi}$$

$$\frac{CR}{B} \propto \gamma^{1/2} Z^{-2/3}$$ at definite conditions Channeling Radiation becomes more powerful than Bremsstrahlung

Channeling Radiation *…one pass to the discovery …*

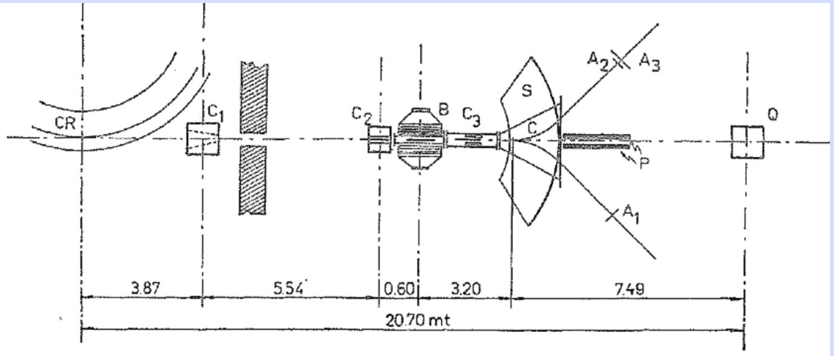


Figure 1. The Frascati Electron Synchrotron Pair Spectrometer

International Journal of Modern Physics A
Vol. 25, Supplement 1 (2010) 1–8

DOI: 10.1142/S0217751X10049876

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ON THE DISCOVERY OF COHERENT BREMSSTRAHLUNG IN A SINGLE CRYSTAL AT THE FRASCATI NATIONAL LABORATORIES

G. BARBIELLINI[1], G.P. MURTAS[2], AND S.B. DABAGOV[2,3]

4. First hint of channeling radiation at LNF

The alignment of the beam from electron bremsstrahlung in the diamond crystal was an experimental procedure done at the beginning of every new run. The image of the beam crossing three collimators $C_{\{1,2,3\}}$ (see Fig. 1) was recorded by a Polaroid film fixed in front of the Wilson Quantameter Q. The beam spot was maximized by moving the collimators, the exposure was done at the fixed electron number on the crystal target. Several of many alignment procedures resulted in a clear over-exposure of the image on the Polaroid film.

In order to define a possible correlation of the image over-exposure with some of the beam parameters, Gian Paolo Murtas were studying this phenomenon. After a long search for the possible source of the over-exposure it was found that the effect is observed every time when the angle between the electron beam and the crystal axis was equal to zero as remained after the previous working run. The correlation was confirmed by many film exposures at the same experimental conditions. The possibility that very soft radiation emission could be coherently stimulated when the electron is crossing the crystal periodic potential at zero angle became clear but within the framework of the coherent interactions in crystals. However, the forward (zero angle) emission was measured by means of one emulsion instead of the main instrument, namely, the Pair Spectrometer. The emulsion was used for a usual procedure of the alignments of the γ-beam with collimators of the pair spectrometer etc, and very bright spots due to soft photons were recorded. The explanation of the observed over-exposure at zero angles with rispect to the main crystallographic axis can be considered as a first experimental hint of the existence of channeling radiation.

The experimental efforts defined a line for both the deeper investigation on a new discovery of the monochromatic and polarized photon production due to CB and the polarization measurements. The lower sensitivity of the spectrometer was 70-100 MeV that was too high for efficient studying channeling radiation spectra for 910 MeV electrons crossing diamond crystals [11].

Crystal based radiators

Channeling Radiation *…one pass to the discovery …*

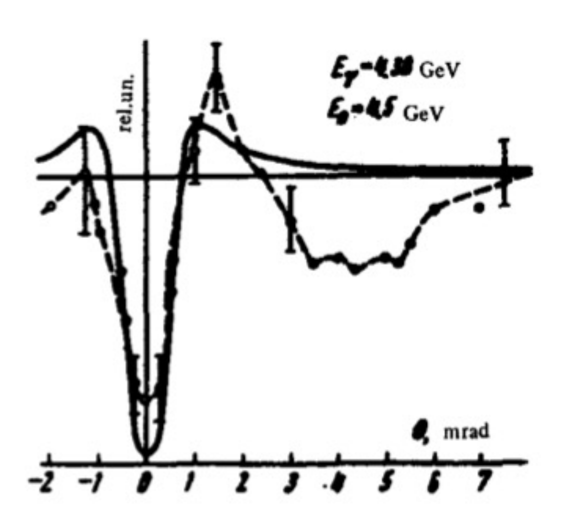
Orientational dependence of the yield of bremsstrahlung photons of maximum energy in crystals

R. O. Avakyan, A. A. Armaganyan, L. G. Arutyunyan, S. M. Darbinyan, and N. P. Kalashnikov

Erevan Physics Institute

(Submitted February 10, 1975)
ZhETF Pis. Red. **21**, No. 7, 451–453 (April 5, 1975)

Experimental and theoretical investigations were made of the orientation dependence of the differential cross section of the bremsstrahlung of hard photons on the entrance angle of ultrafast electrons into a single crystal. A strong decrease of the yield of bremsstrahlung photons with maximum energy near zero entrance angle is predicted and observed.



Theoretical works by Thomson, Kalashnikov, Baryshevsky & Dubovskaya, Vorobiev

…one pass to the discovery of Channeling Radiation…

Crystal based radiators

Channeling Radiation *…discovery…*

… long 4 years distance…

SLAC experiment of USA (resp. Panovsky)
USSR (resp. *Kumakhov*) joint experiment 1979.

Experimental study of radiation of channeled relativistic positrons

I. I. Miroshnichenko, J. J. Murray,[1] R. O. Avakyan, and T. Kh. Figut

(Submitted 9 April 1979)
Pis'ma Zh. Eksp. Teor. Fiz. **29**, No. 12, 786–790 (20 June 1979)

The energy spectra of electromagnetic radiation produced as a result of interaction of high-energy positrons with crystals under conditions of planar and axial channeling were measured for the first time. A new physical effect was observed—radiation of channeled relativistic positrons—which was theoretically predicted by the Soviet physicist M.A. Kumakhov.

"Kumakhov Radiation" <-> "Kumakhov Effect"

Crystal based radiators