Trends and Perspectives for Channeling Physics

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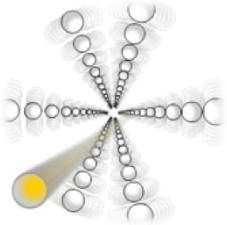
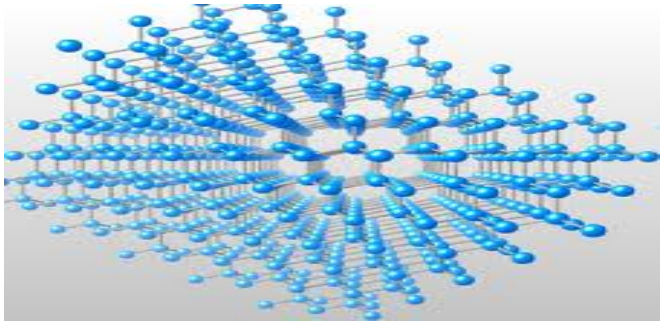
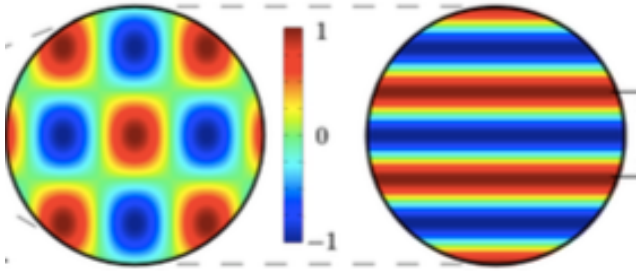
Channeling: from Crystal to Capillary guides

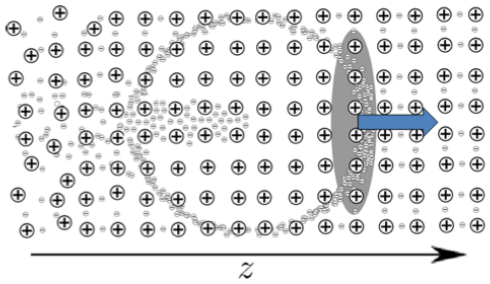


- Crystal Channeling
  - beam shaping
  - micro-undulator

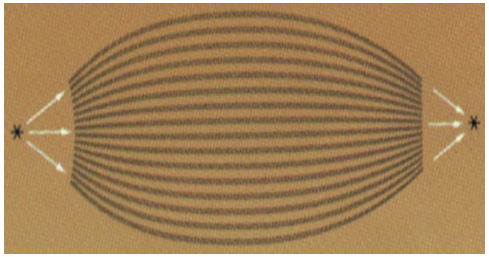


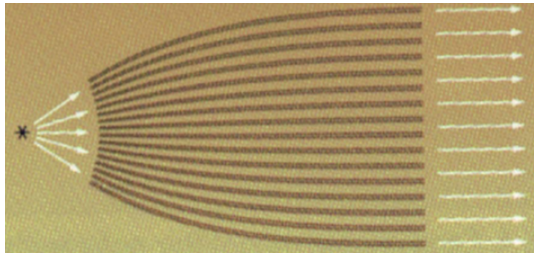
- Laser & Plasma Channels

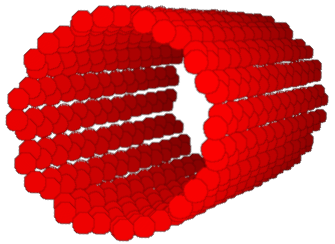




- Capillary Micro- & NanoChannels



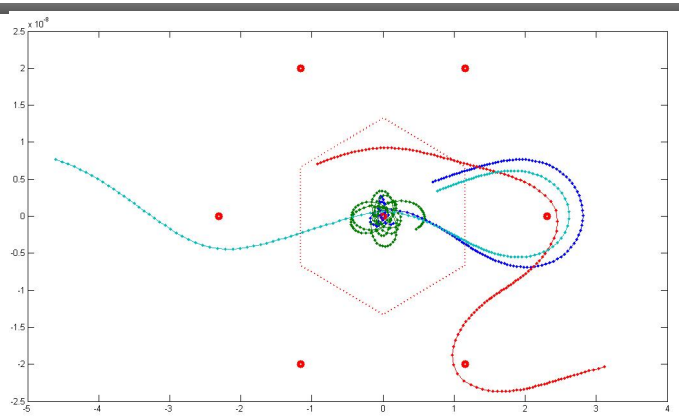




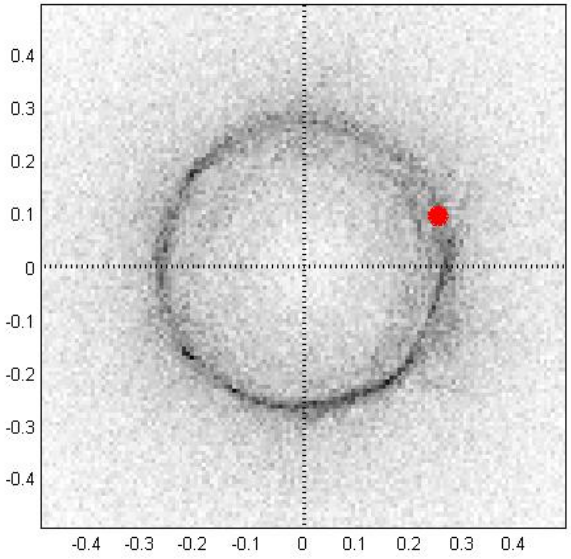
@ Electron channeling studies at SPARC energies: simulations

Ge <111>
150 MeV

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



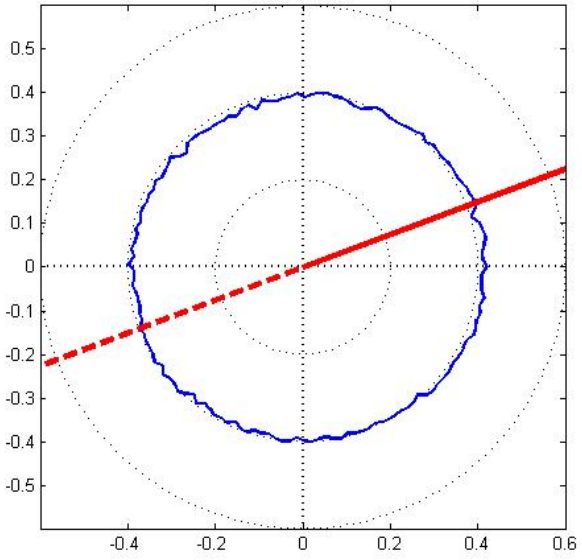
various trajectories transverse axis cross-section



$\Delta\theta$ = 0 – beam divergence
θ_0=0.25 θ_c – incidence angle

depth evolution
Δt = 81 nm ÷ 1.33 μm

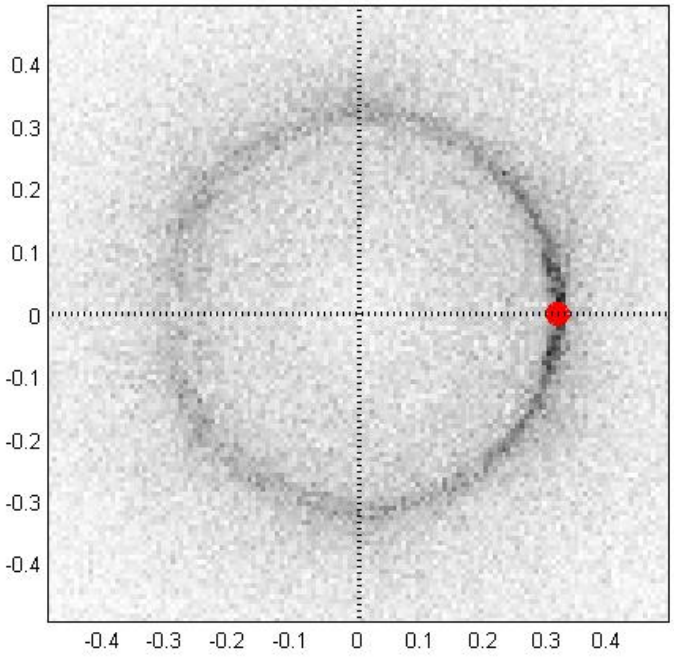
The efficiency of "reflection" in optimized conditions becomes rather high

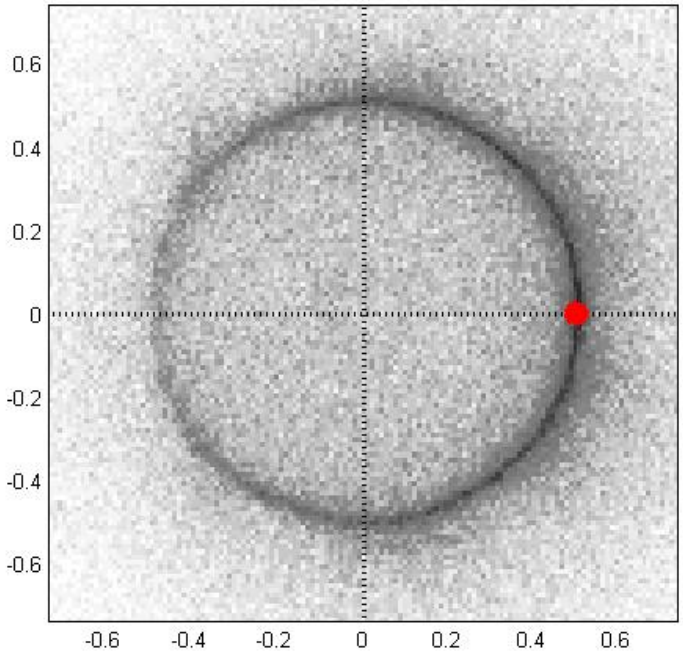


@ Electron axial channeling in a thin Ge crystal: simulations

Ge <111>
150 MeV

Δθ = 0 – beam divergence
Beam thickness evolution
Δt = 81 nm ÷ 1.33 μm



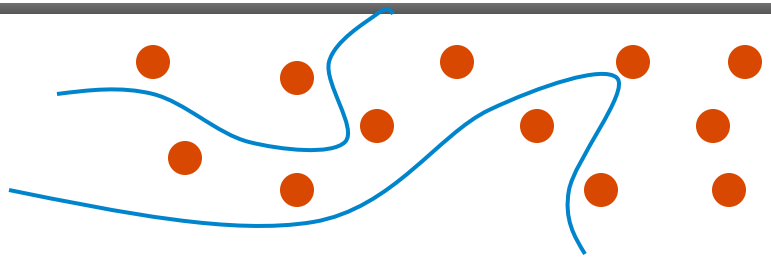


$\theta_0=0.32\ \theta_c$ *– incidence angle*

$\vartheta_0=0.5\ \vartheta_c$ *– incidence angle*

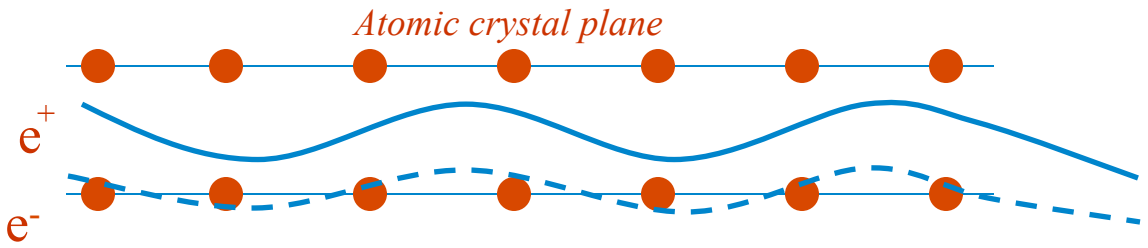
@ Channeling of Charged Particles

@ Amorphous:

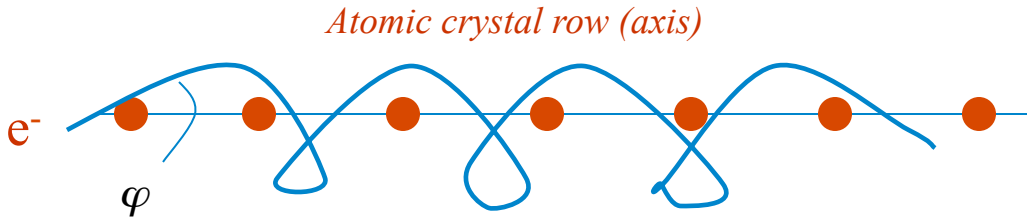


@ Channeling:

planar channeling



axial channeling

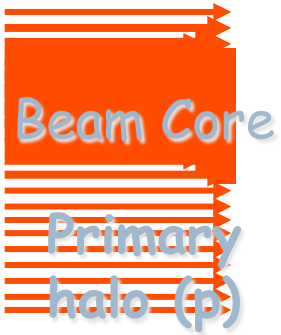


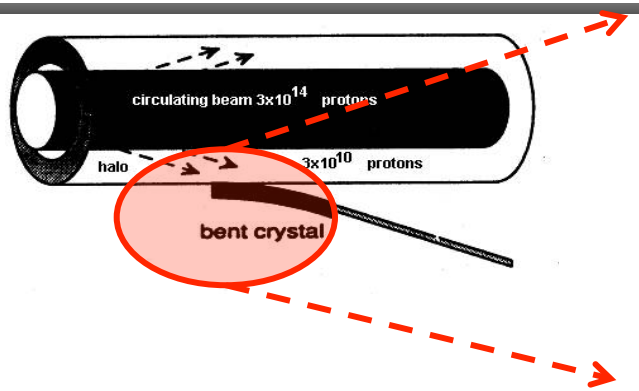
$\varphi << 1 \qquad (\varphi < \varphi_L \sim \sqrt{U/E})$ - *the Lindhard angle is the critical angle for the channeling*

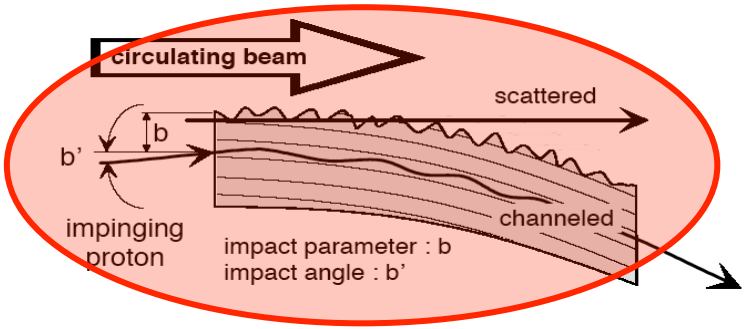
EuCARD²

@ Beam Collimation & Extraction

@ Crystal collimation at CERN

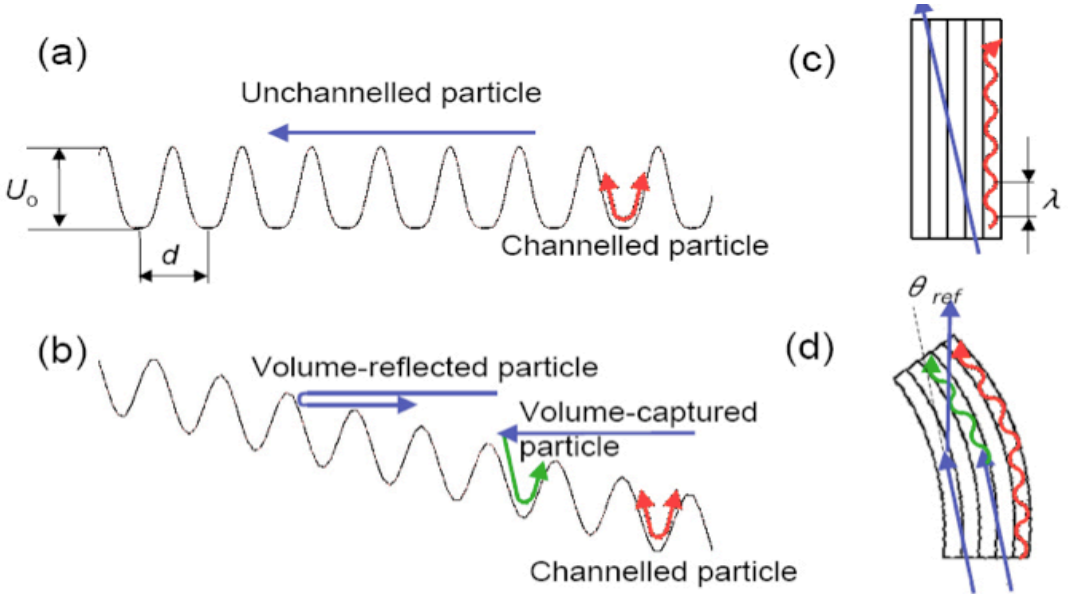




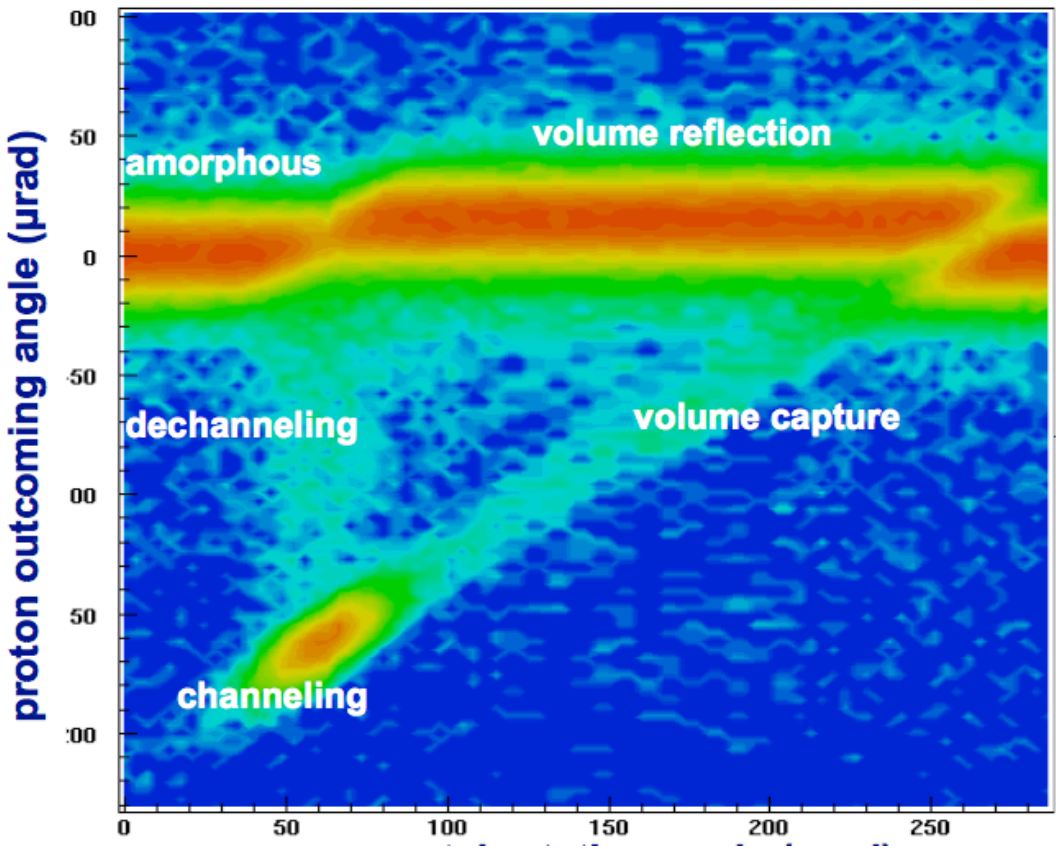


Possible processes:

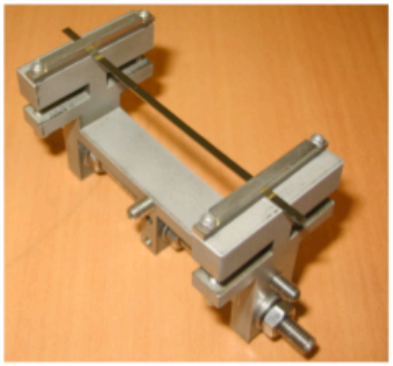
- multiple scattering
- channeling
- volume capture
- de-channeling
- *volume reflection*



@ First observation: 400 GeV/c CERN



Single strip crystal

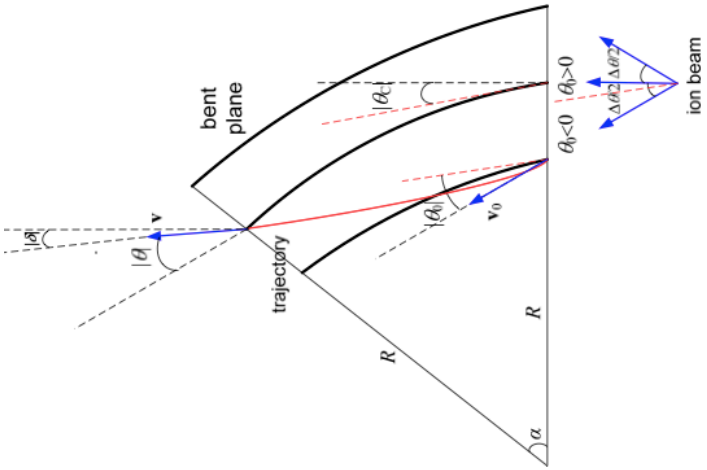


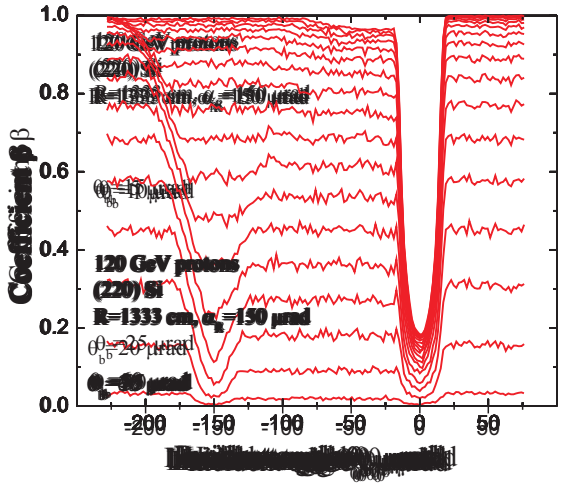
- *First measurement* of the volume reflection effect with a proton beam of 400 GeV/c

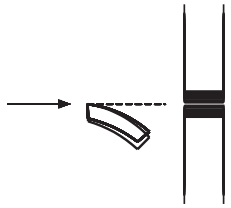
EFFICIENCY	VALUE
VOLUME REFLECTION	98.2 ± 0.1%
CHANNELING	51.2 ± 0.7%
VOLUME CAPTURE	1.3 ± 0.1%
DECHANNELING	5.0 ± 0.4%

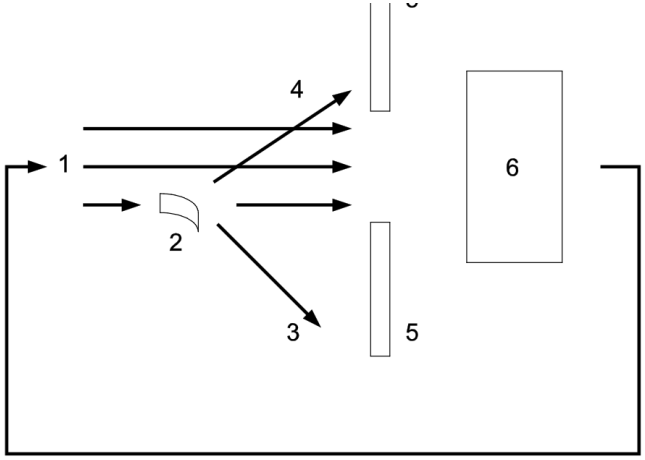
Multi-strip technique is under strong investigation

EuCARD² @ Proton multiple passage features









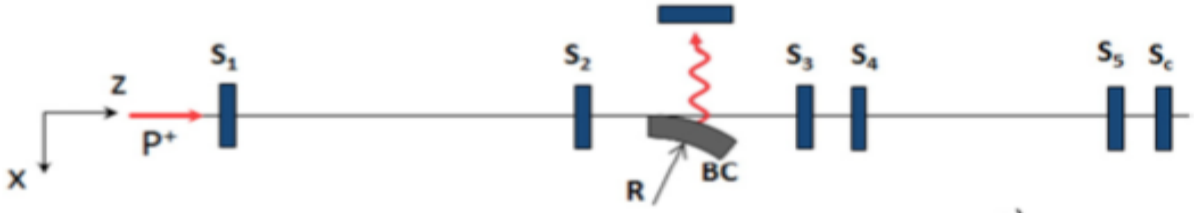
Experimental setup scheme:

1 – the initial parallel proton beam,
2 – the bent crystal,
3 – the channeled protons,
4 – the reflected protons,
5 – the absorber,
6 – the focusing system.

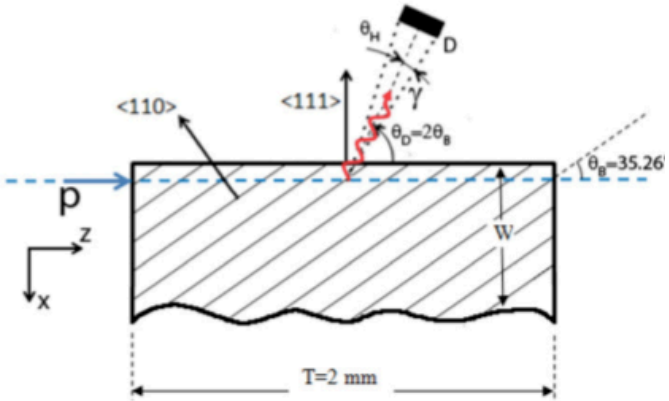
… alignment on μrad level is very important …

EuCARD²

@ PXR for the alignment/crystal diagnostics



a)



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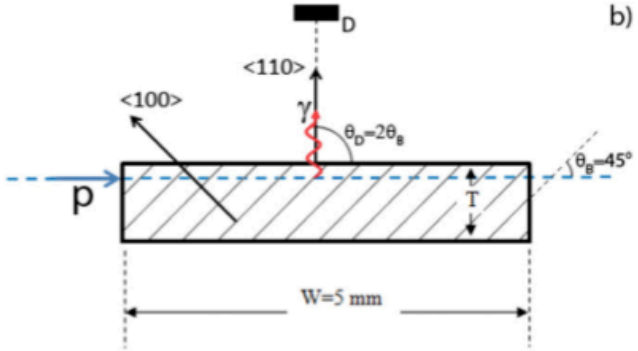
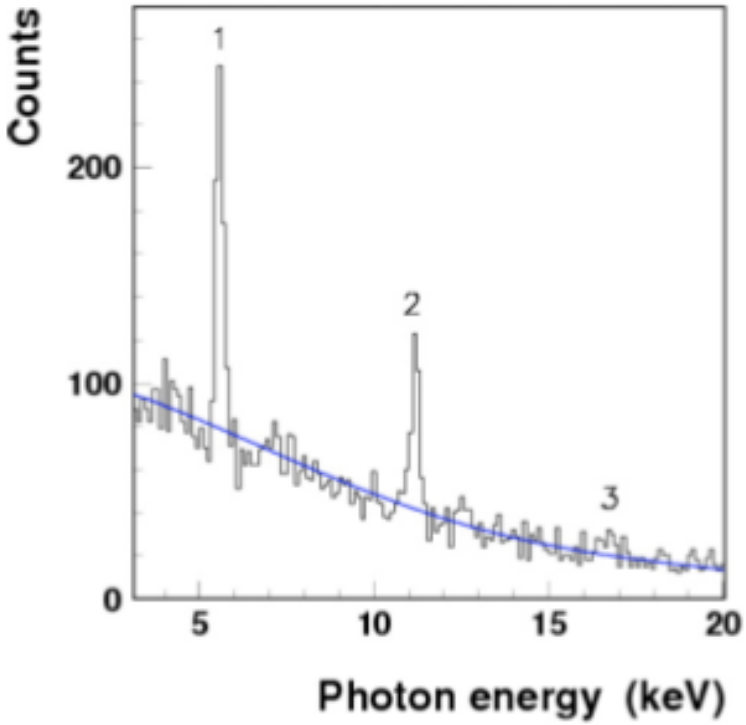
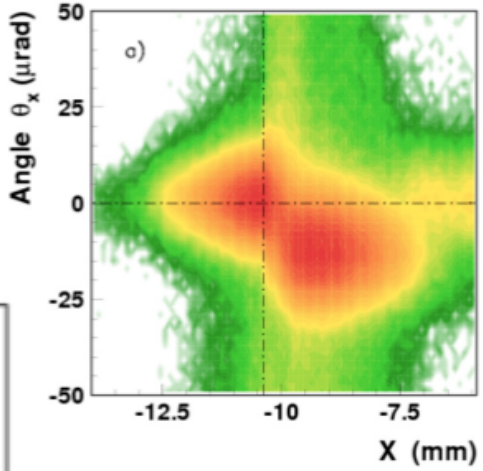
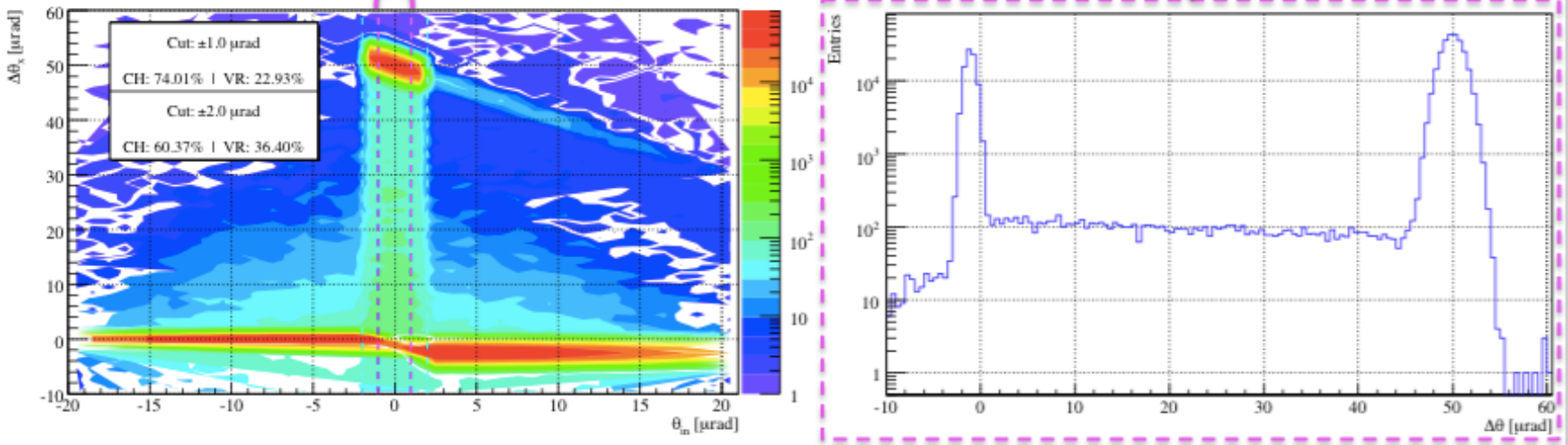






EuCARD² @ deflection efficiency for TeV energies

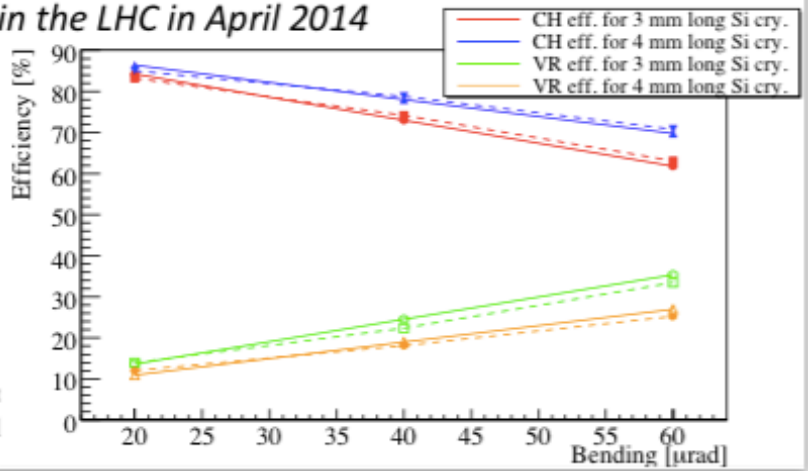
Simulated deflections & efficiency for crystals installed in the LHC: 4 mm long, 50 µrad bending
Gaussian beam of 7 TeV with σ_x=1mm, $\sigma_{x'}$=10µrad.



Parametric comparisons made with respect to Taratin's code at 7 TeV for studies related to the choice of crystals installed in the LHC in April 2014

7 TeV beam with a uniform distribution ±1 µrad.
Trend of CH & VR efficiency are compared.

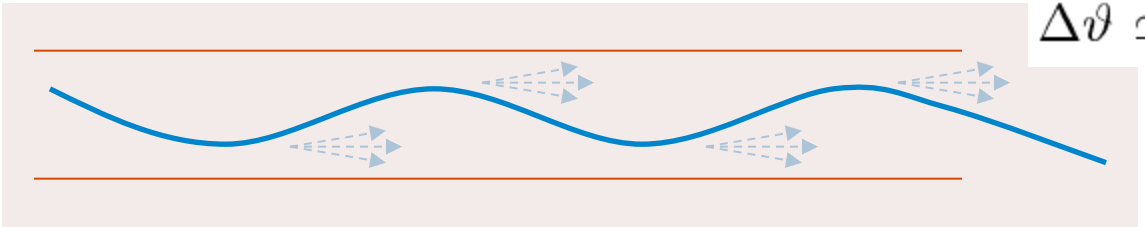
Dashed line: **Fully analytical crystal simulator**
Solid line: **Crystal emulator in SixTrack**



@ Channeling of Charged Particles & Channeling Radiation

@ Channeling Radiation:

$$\omega = \omega(\theta) = \frac{\omega_{fi}}{1 - \beta_{\|} \cos\theta}$$

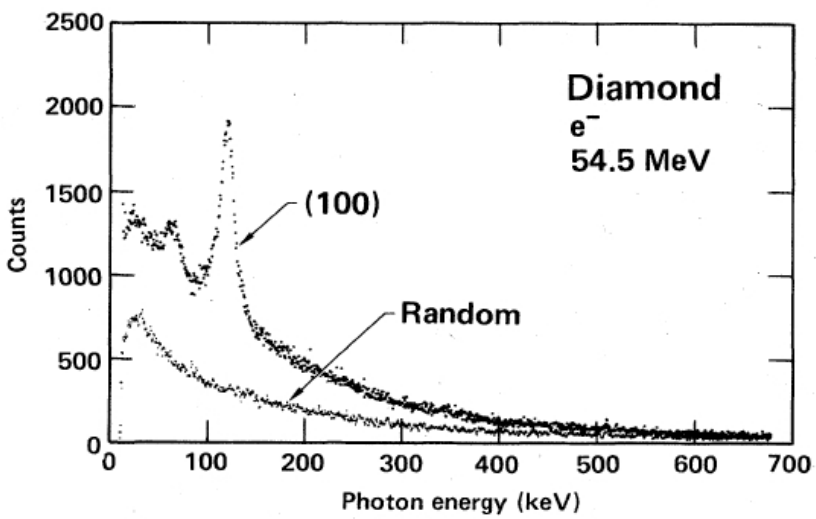


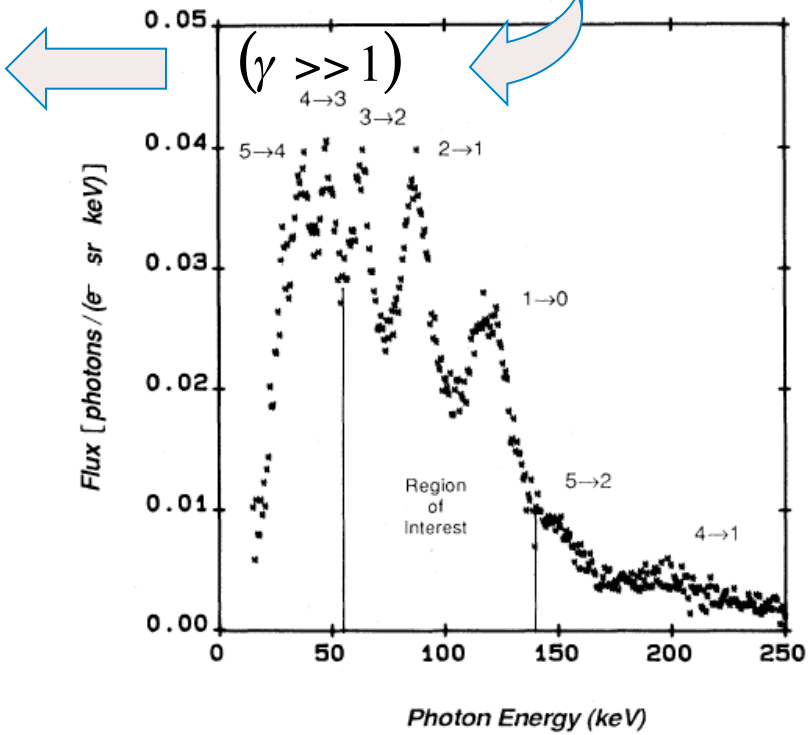
$\Delta\vartheta \simeq \gamma^{-}$

ω_{fi} - *optical frequency* → *Doppler effect* → $\omega_0\gamma^{3/2}$ - $\omega_0\gamma^2$

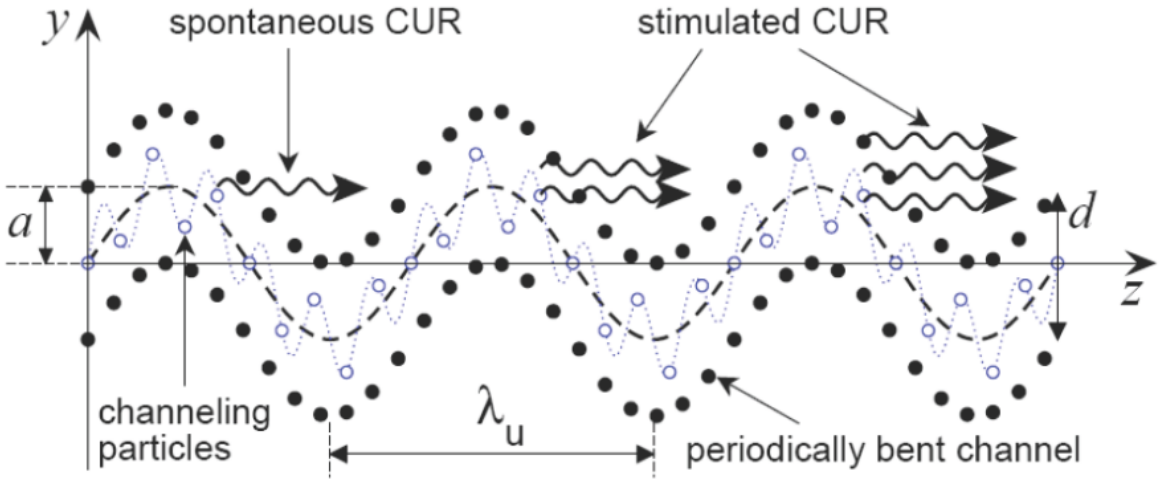
Powerful radiation source of X-rays and γ-rays:

- polarized
- tunable
- narrow forwarded





EuCARD² @ Crystalline Undulator



combination of ChR & CUR:

frequncies are shifted

d=1…2 Å – the interplanar spacing
a=(1…50)*d* – the amplitude of bending
λ_u=10…100 μm – the period of bending

$$d << a << \lambda_u$$

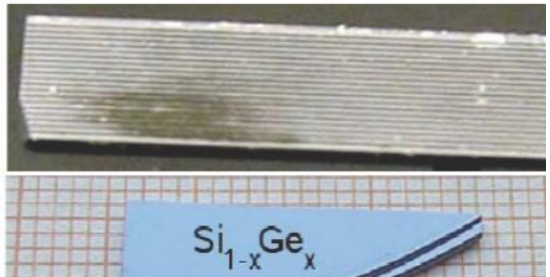
huge scale factor →

Magnetic undulator:

λ_u~1 cm, ħω~10 keV

Crystalline undulator:

λ_u~10 μm, ħω~0.1 …10 MeV



EuCARD²

@ Novel activities

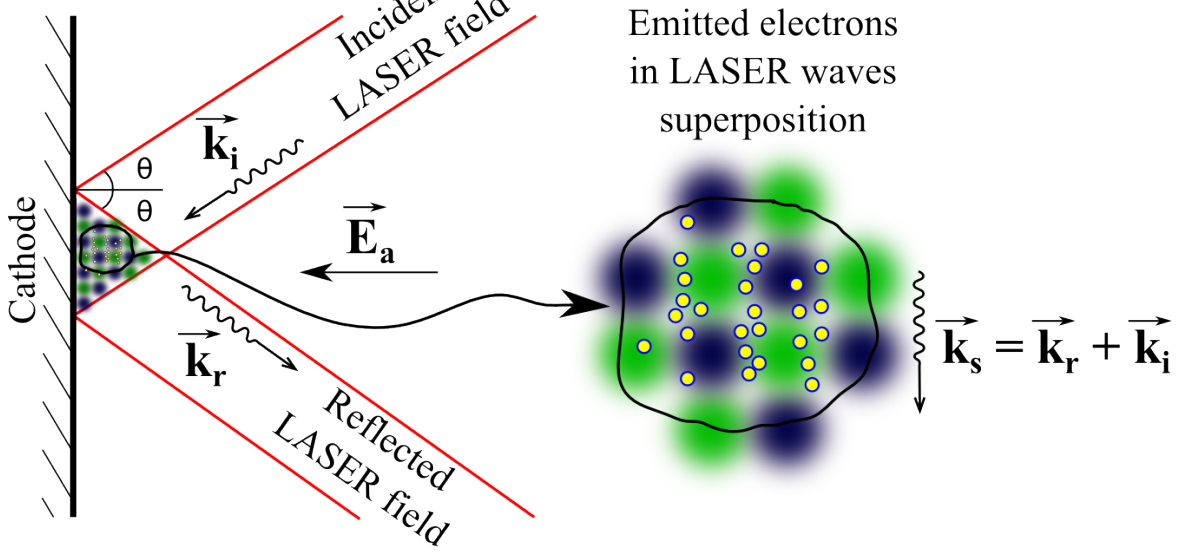
- application for 3-7 GeV electron channeling /**experiment** & **theory**/
  - beam deflection
  - VR based radiation
  - crystalline undulator

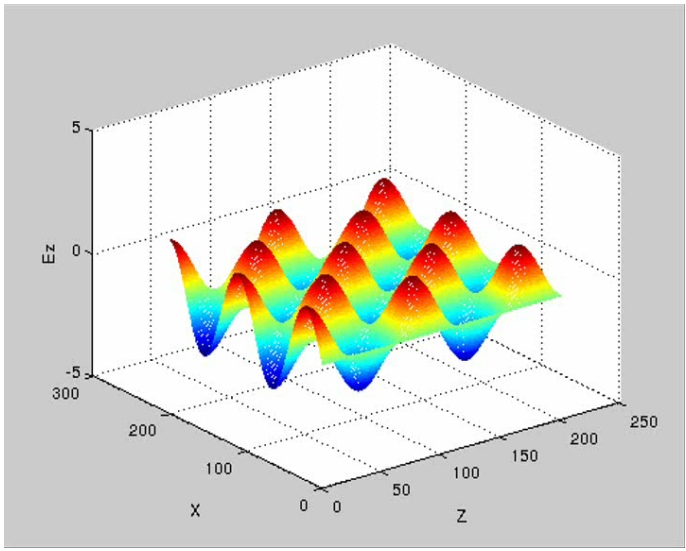
- crystal-laser & CNT based nanoscale accelerator /experiment & **theory**/
- TeV hadron beam extraction /**theory**/
- channeling as a tool for new positron source /experiment & **theory**/

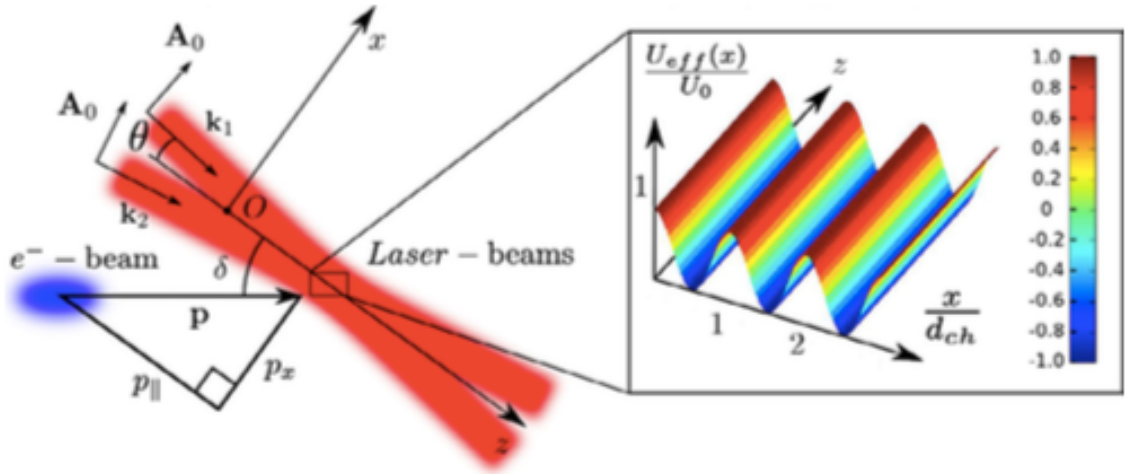
EuCARD²

@ Laser & Plasma Channels

EuCARD² @ Channeling in crossed laser field







@ Potential well forming

Effective potential and entrapment requirement

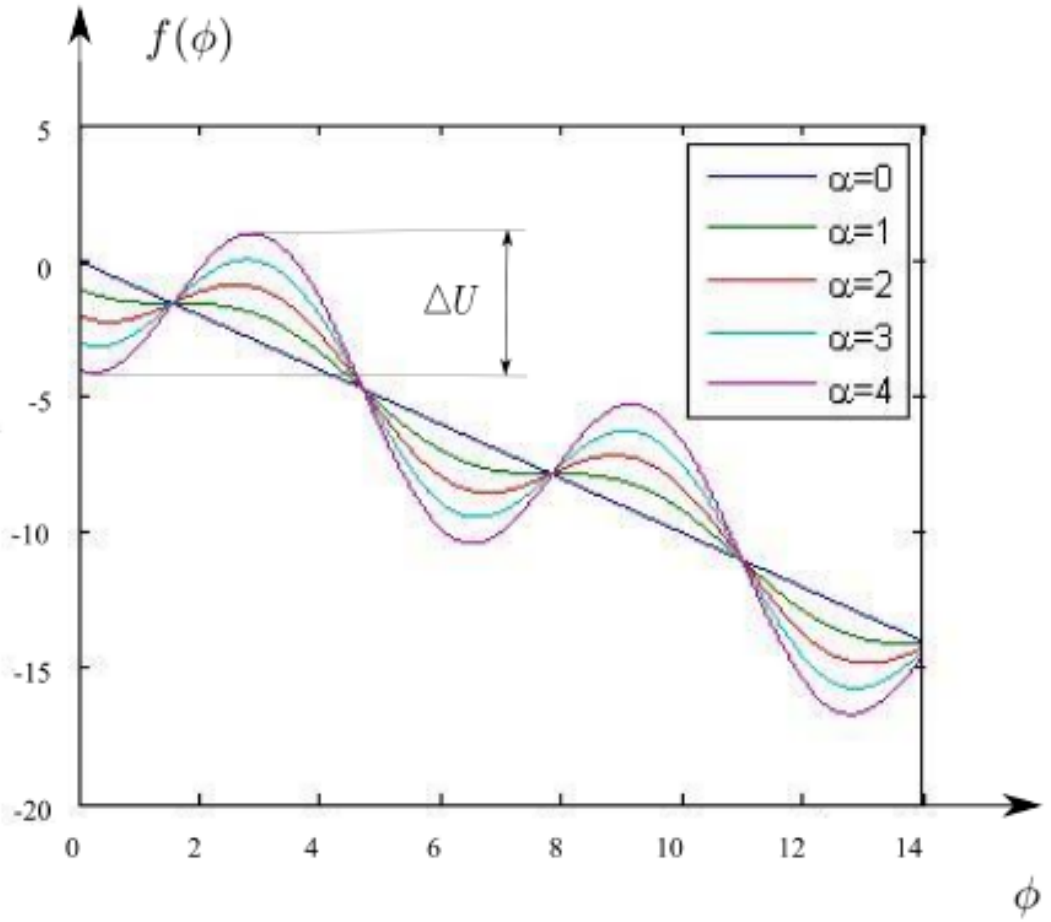
$$f(\phi) = \frac{U_{eff} 2k \cos\theta}{eE}$$

$$\phi = 2kz \cos\theta$$

$$\alpha = \frac{eE_0^2 \sin^2\theta k \cos\theta}{m\omega_0^2 E}$$

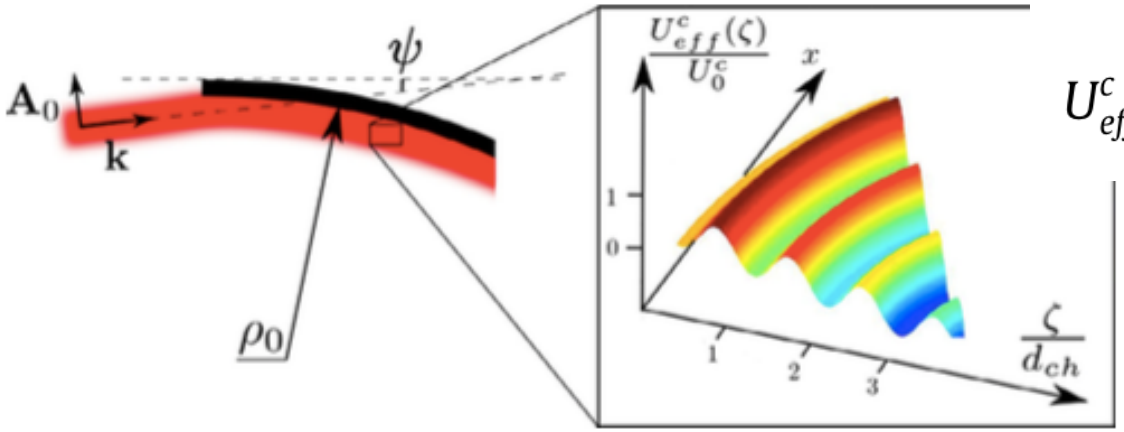
Necessary condition of bound state occurrence

$$\alpha > 1$$



strong dependence on laser and beam parameters

@ Effective Potential of Curved Laser Channels

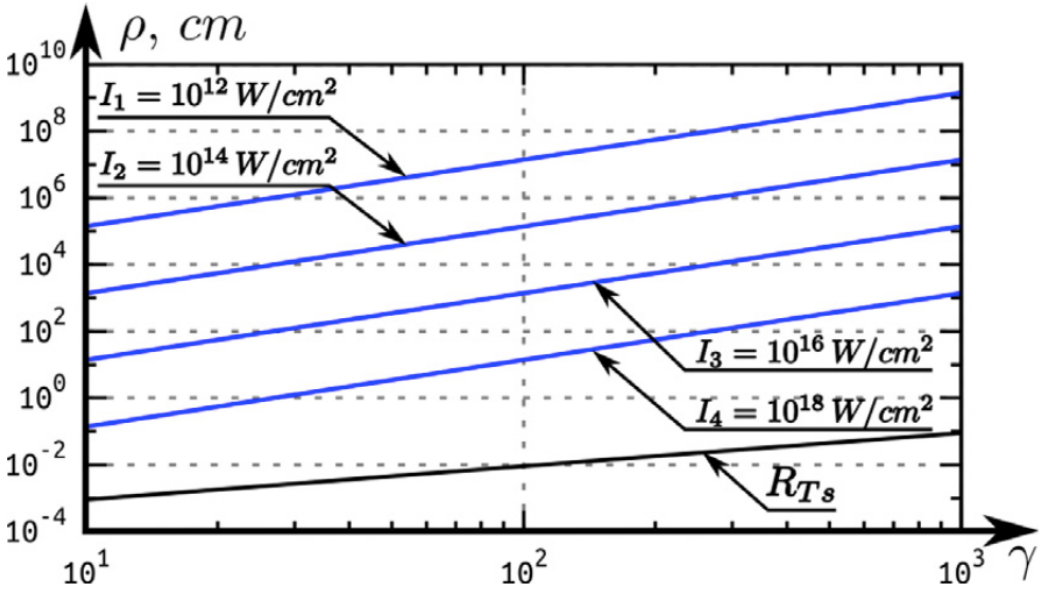


$$U^c_{eff}(\bar{\zeta}) = \frac{e^2 A_0^2}{8mc^2\bar{\gamma}} \cos(2k\psi\bar{\zeta}) - \frac{\bar{\gamma} m v_0^2 \bar{\zeta}}{\rho_0}$$

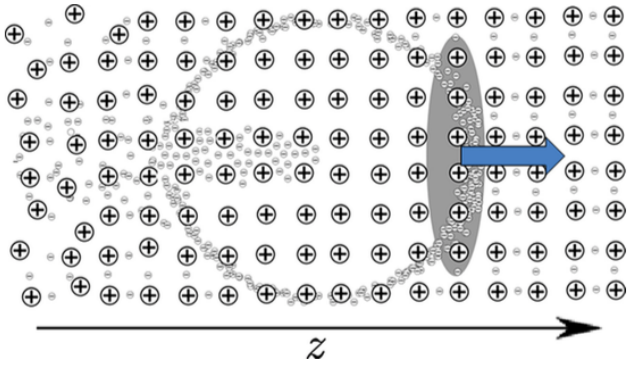
effective potential of curved laser channel

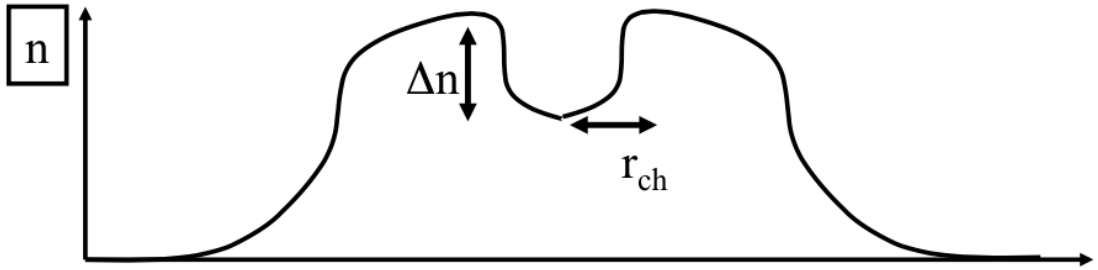
$$\rho_{cr} = \frac{4(m\bar{\gamma}c^2)^2}{e^2 A_0^2 k\psi} \approx 1.6 \cdot 10^{-8} \left(\frac{m\bar{\gamma}c^2}{e}\right)^2 \frac{\omega_0}{\psi I}$$

critical radius for e- steering in curved laser field

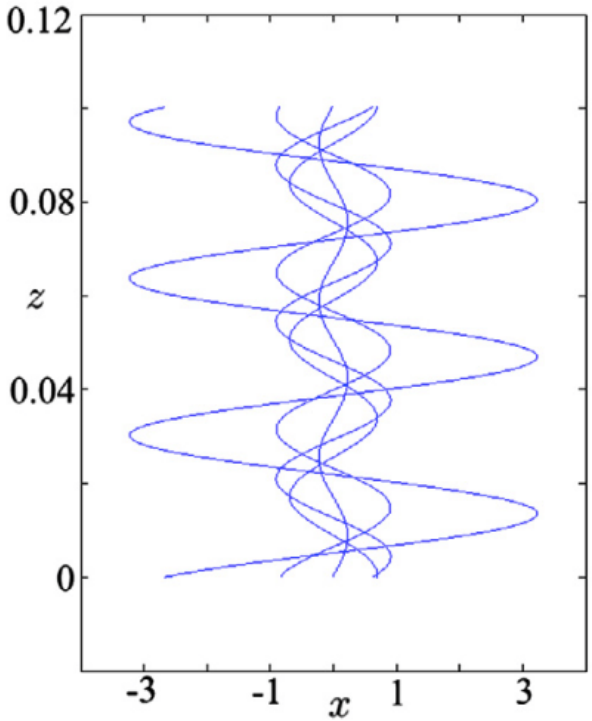


EuCARD² @ Laser based Plasma Channel

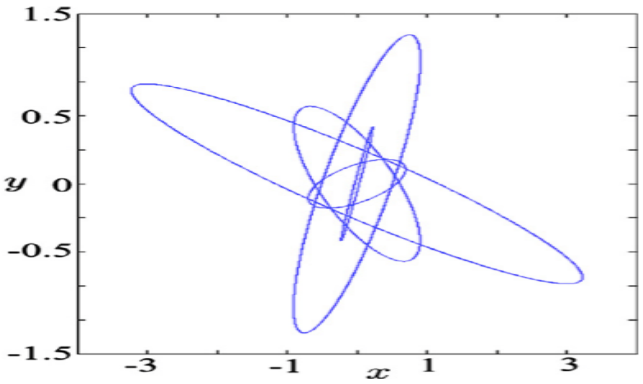




$$w_0 = \left[r_{ch}^2 / (\pi r_e \Delta n) \right]^{1/4}; \quad r_e = e^2 / mc^2$$



The laser pulse propagates in a plasma channel acting as a focusing lens that counter-balances the diffraction effects. For the optimal channel shape, laser pulses can be guided over distances exceeding several Z_R.



…channeling method simplfies calculations…

EuCARD²

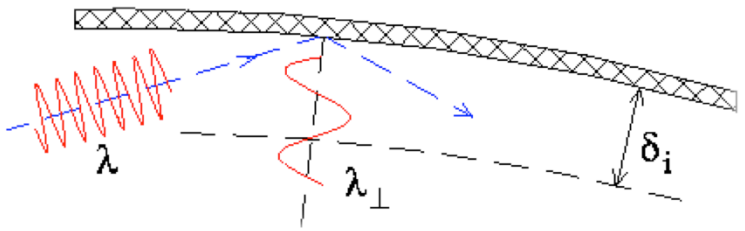
@ Capillary Micro- & NanoChannels

@ Modes of channeling along curved surfaces

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

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

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



Effective guide channel $\Rightarrow$ $\delta_i(\theta) \simeq \lambda_\perp(\theta)$

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

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

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

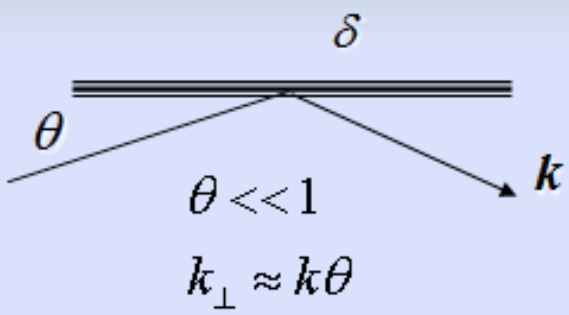
$$\lambda \simeq 0.1 \div 10\ \text{Å}$$

Upper limit of the curvature radius

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

$$\lambda \sim 1\ \text{Å}$$

Very important expression for the diffraction limit estimation – can be applied for any kind of the optics:

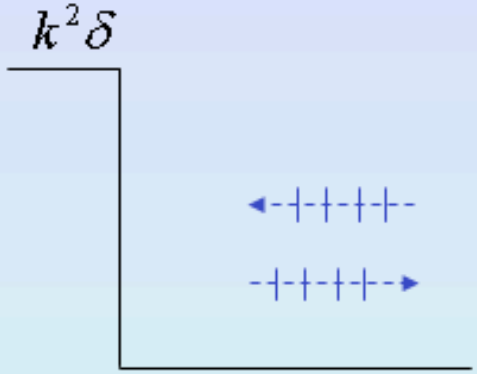


1st order: $\Delta\varepsilon(\vec{r}) = 0$ *- no roughness*

Wave equation:

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

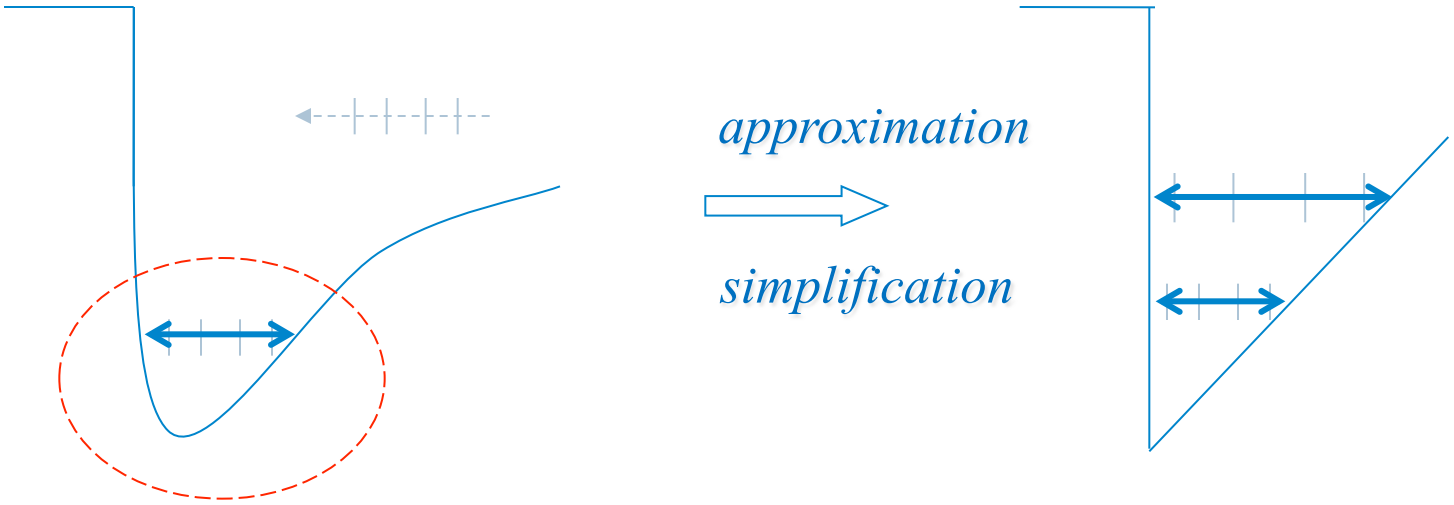
$$k^2\left(\delta(\vec{r}_\perp) - \theta^2\right) = \begin{cases} -k^2\theta^2, & r_\perp < r_1 \\ \underbrace{k^2\left(\delta_0 - \theta^2\right)}, & r_\perp \geq r_1 \end{cases}$$



plane (flat) surface

Total external reflection

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



additional term to

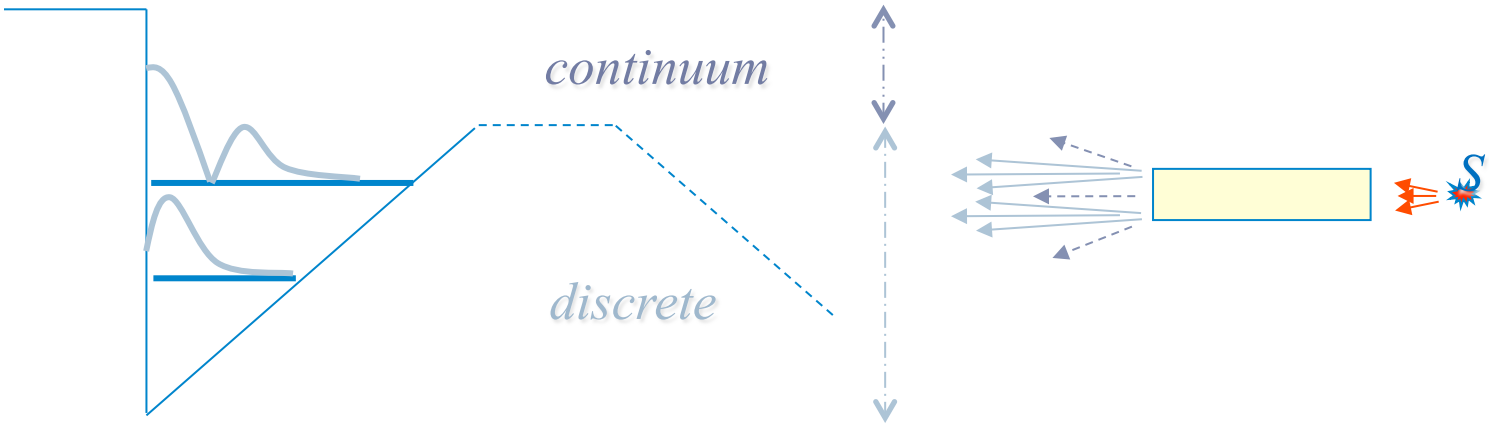
V_{eff} → $2\dfrac{-k^2 r_\perp}{r_{curv}}$

"potential energy": angular momentum of photon

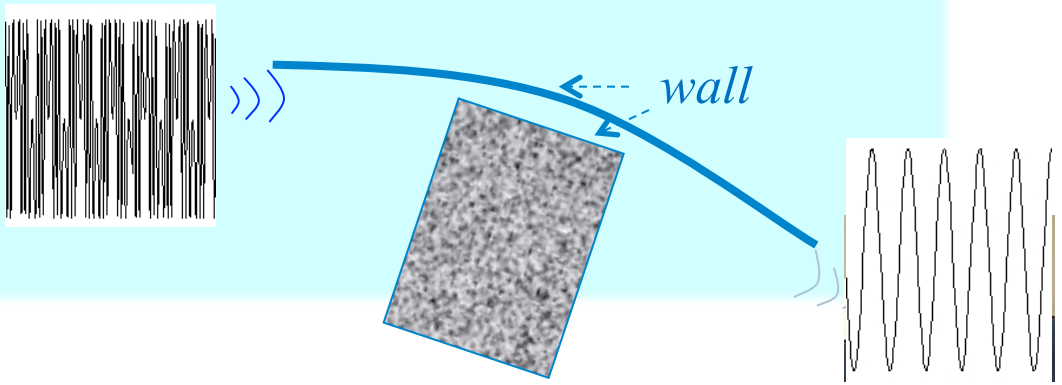
$kr_{curv}\varphi$

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

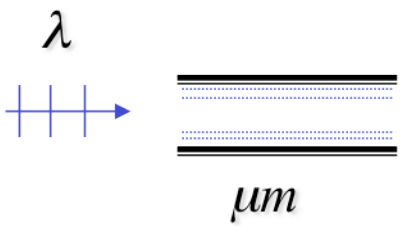
@ Surface channeling - *"whispering X gallery"*



* *Whispering:*



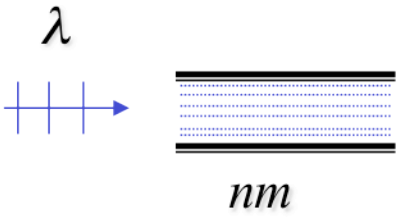
EuCARD² @ Down to bulk X-ray channeling



$\theta << 1 \quad (\theta_c \sim 10^{-3})$: *grazing incidence optics*

$\lambda \quad \rightarrow \quad \lambda_\perp >> \lambda$: *from nm to μm*

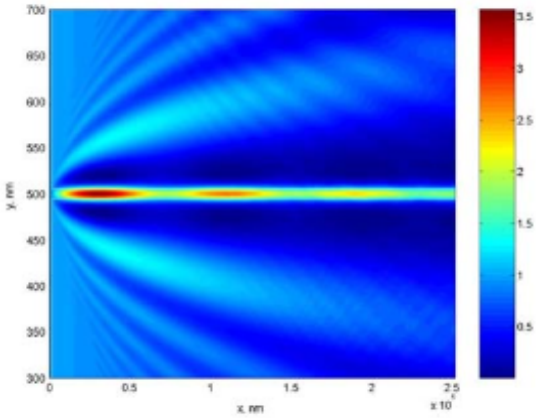
$d_0 \sim 1\mu m \div 10\mu m: \quad \lambda_\perp << d_0$: *surface channeling*



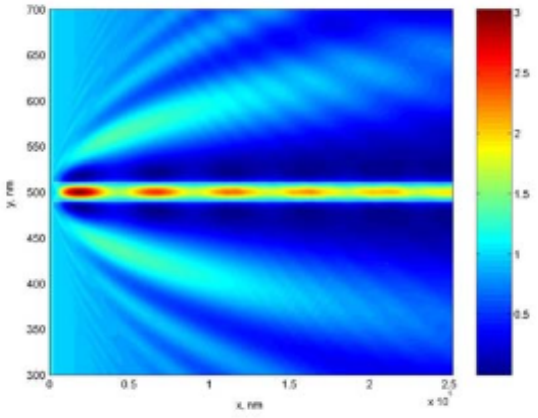
$\theta_d = \lambda / d_0 \sim \theta_c$: *diffraction angle approaches Fresnel angle*

$\lambda_\perp / d_0 \sim 1$: *bulk channeling*

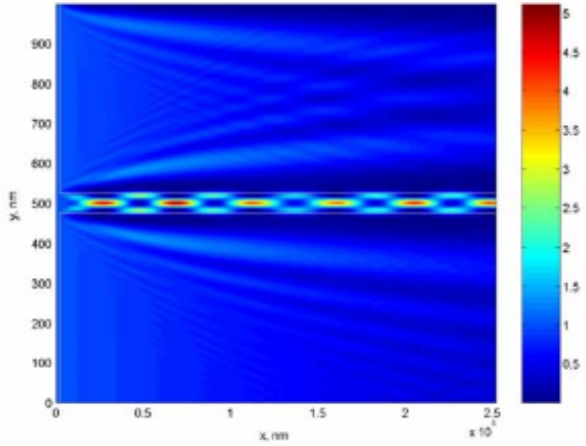
@ Nanocapillaries



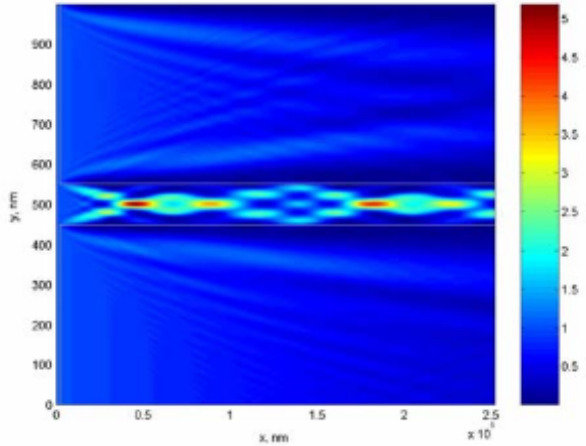
Width 10 nm



Width 20 nm



Width 50 nm



Width 100 nm

Wavelength 0.1nm, material Si, length 2*Labsorb=2.5e5 nm

$$\varsigma = \frac{2\pi\theta_c a}{\lambda} \equiv \frac{2\pi a}{\lambda_{\perp c}}$$

- number of modes

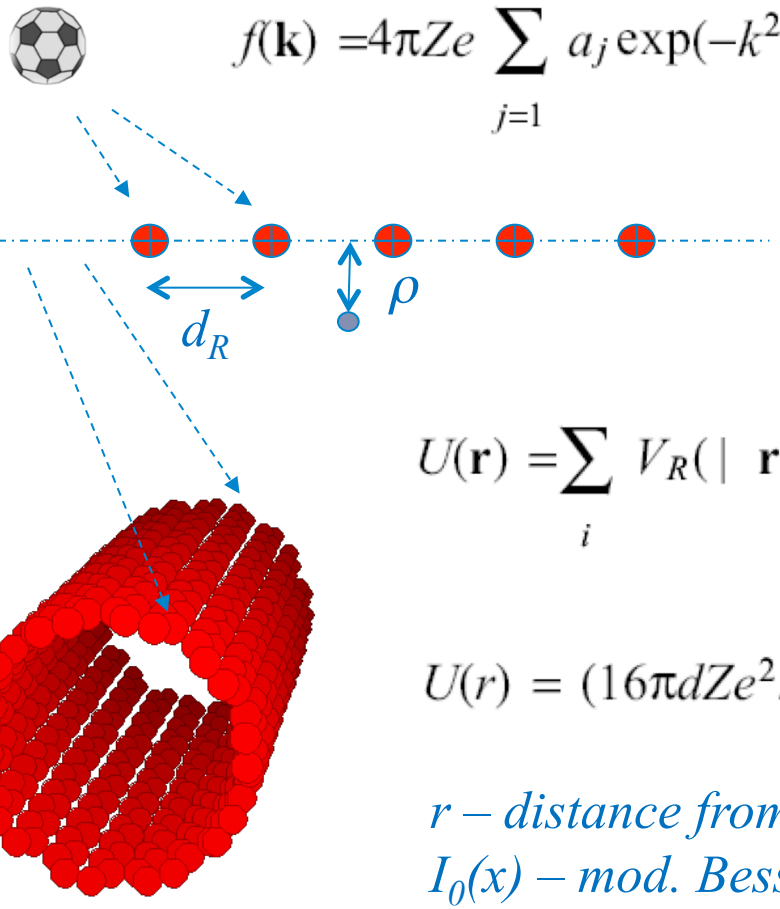
$$\lambda_{\perp c} \cong \lambda/\theta_c$$

~ 40 nm for glass

Tunneling length

$$\propto \frac{c}{\omega_p} \approx \frac{137e^2}{\omega_p} \approx 8 \ nm$$

@ Channeling Potential for a Nanotube



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

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

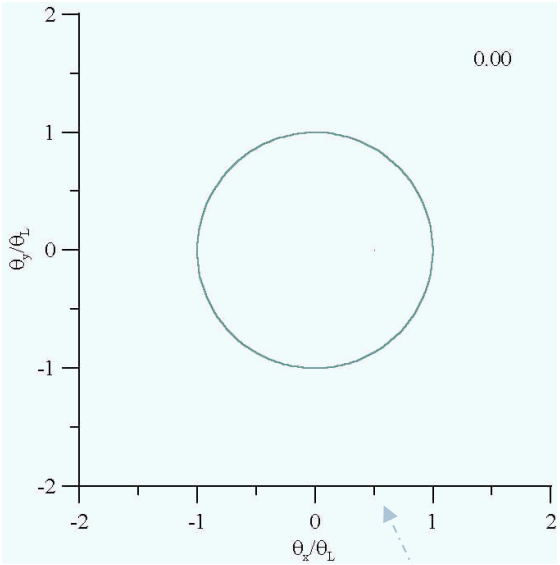
r – distance from the tube

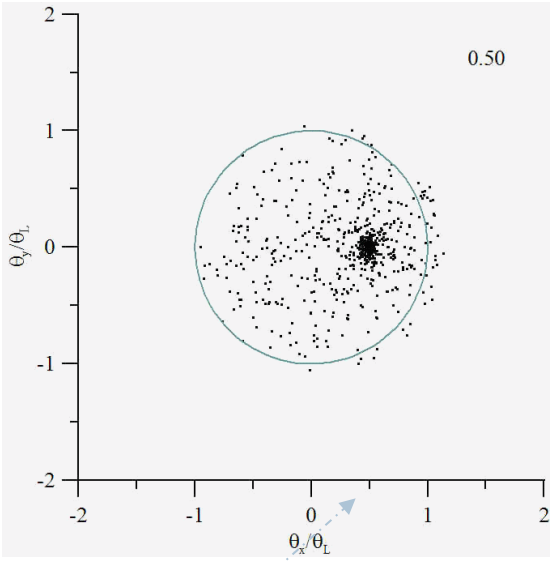
$I_0(x)$ – mod. Bessel function

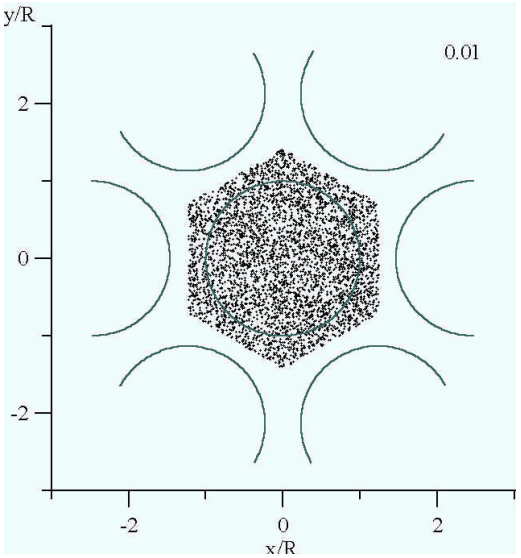
@ Simulations for photon-neutron channeling (straight & bent)

Angular distributions

Spatial





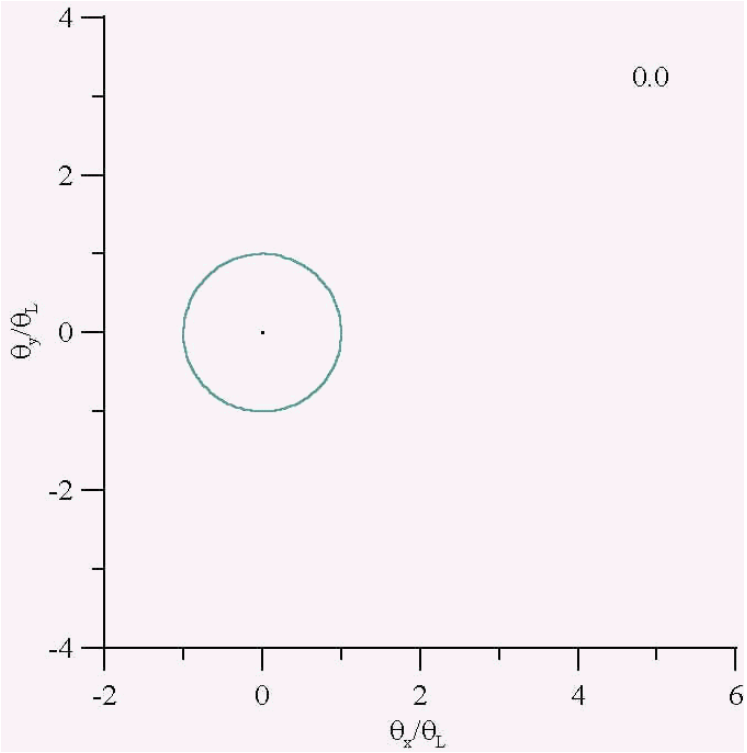


Coherent scattering: $0\text{-}L_0$

Multiple reflections: $L_0\text{-}20L_0\text{-}10^3L_0$

Angle of incidence – 0.5 critical angle of channeling

@ Simulations for photon-neutron channeling: bending of radiation



Evolution of angular distribution

$r_{curv} \sim 2\ m$:

Strong bending effect

@ Channeling… future …

- Collimation & Extraction of GeV/TeV hadrons
- Lepton beam shaping (deflection, collimation)
- Crystal Channeling & Channeling related Radiation Phenomena

(applications for e-/e+)

- Channeling in Combined Laser fields
- Channeling based phenomenology of known physical processes

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

- Channeling of Charged Beams and various Radiations in

Capillary/Polycapillary structures (compact storage rings, various x-ray & thermal neutron applications)

- Channeling Phenomena in Nanochannels (TeV/m Nanoaccelerators)

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