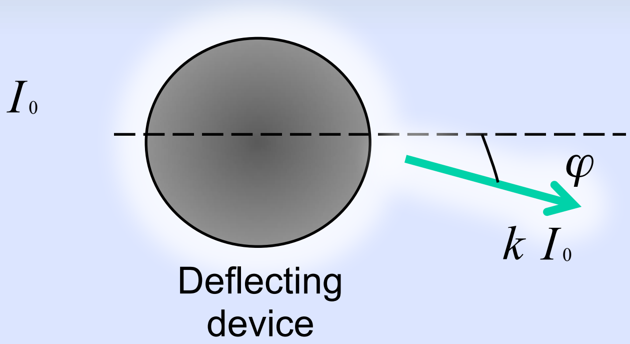
XLab Frascati LNF

Polycapillary Optics:
from Idea to Technology

Focal plane concentrators based on Kumakhov Lenses: possible use in IAXO

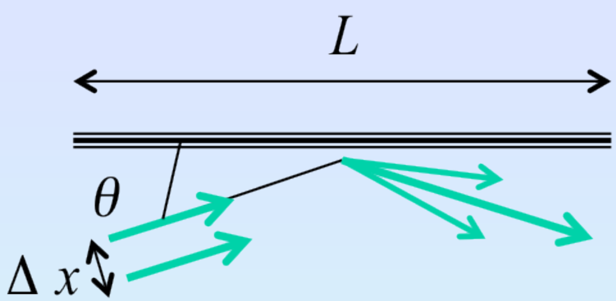
Sultan B Dabagov

@ X-ray Optics Problem



$$k \equiv k(\varphi) \ll 1$$

$$k_{\max}(\varphi) \propto 0.1 \div 0.2$$



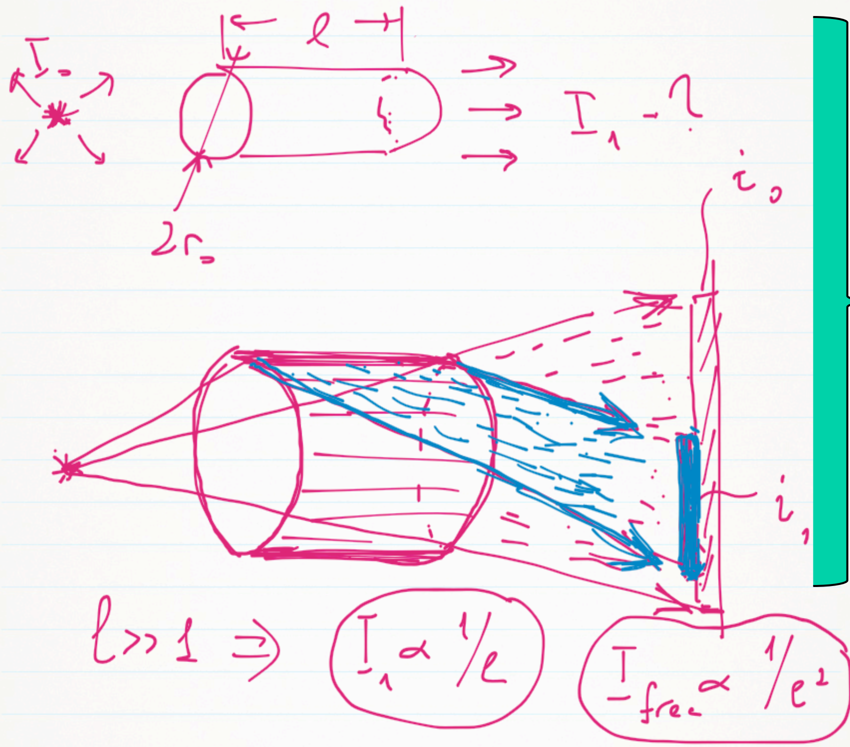
$$\theta \ll 1 \qquad (\theta \le \theta_c \equiv \omega_p/\omega)$$

$$k(\theta) \approx 1$$

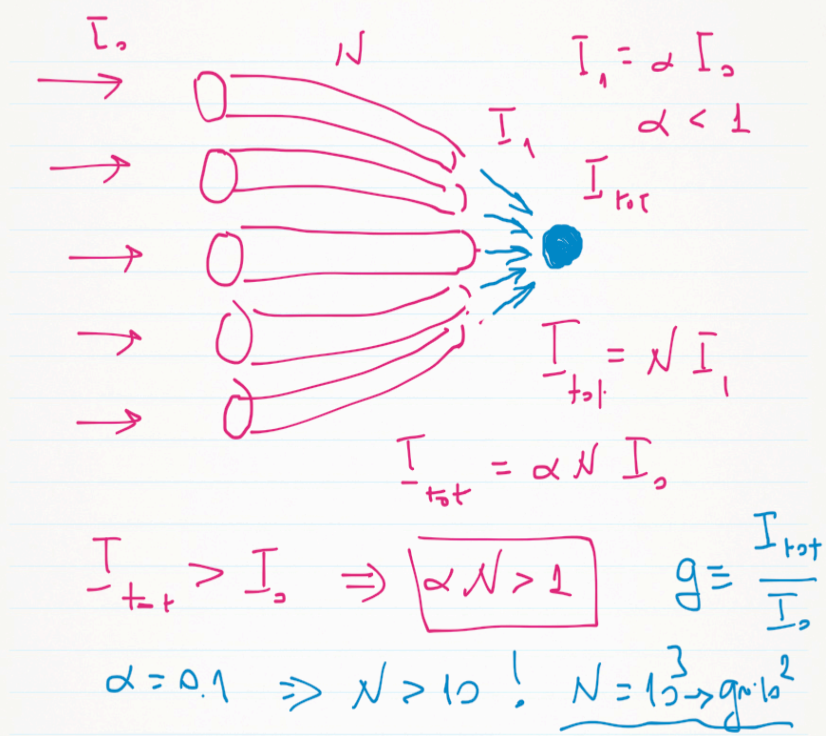
$$\left.\begin{array}{l} \omega \approx 10\ keV \\ \Delta x \approx 1\ mm \end{array}\right\} \rightarrow \quad \varphi \approx 1^{o} \quad \Rightarrow \quad L \ge \frac{\Delta x\, \varphi}{\theta_c^2} \approx 2\ m$$

The system sizes may be significantly diminished (in about two orders of magnitude) by the use of capillary systems.

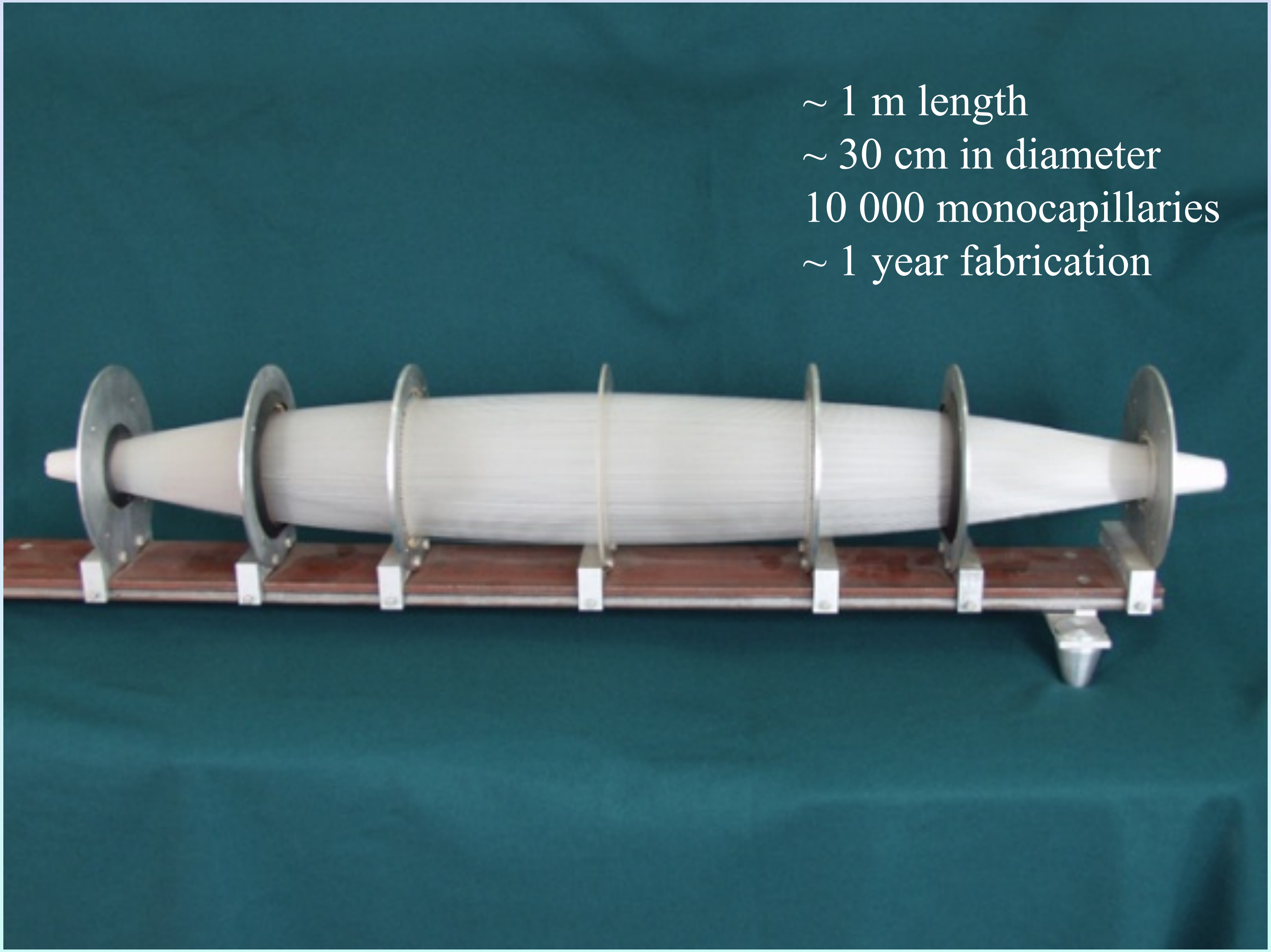
@ 1984: first discussion on polyCO at the Minsk's School on charged particles interaction in crystals



Kumakhov's task:
a night work for the feasibility of mono/multichannel optics



@ 1986: first polyCO => monocapillary semifabricated lens



@ Channeling 2004: idea of XLab Frascati

Sultan Dabagov:

- it would be nice to establish a channeling+polyCO dedicated lab…

Sergio Bertolucci:

- why not? even more, I know where

)) G5+:

- Giordano Diambrini-Palazzi
- Herbert Uberall
- Richard Hoover
- Muradin Kumakhov
- Antonio Longoni
- +

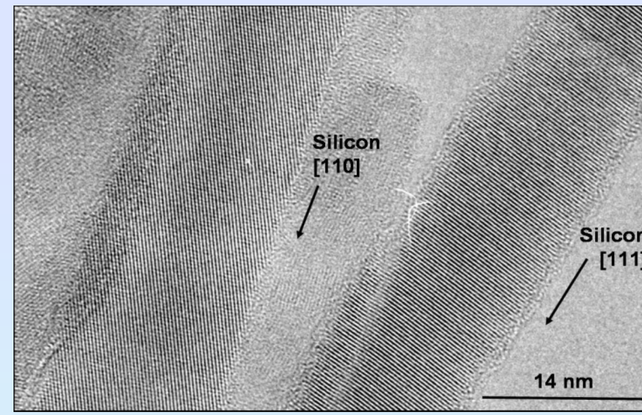
@ polyCO Evolution: "from micro- down to nano"

Generation	Kind of optics	Sizes: length & channel & energy
• 1st	*Assembled lens made of single capillaries*	*1 m & 1 mm & ≤ 10 keV*
• 2nd	*Monolithic lens made of single capillaries*	*10-30 cm & 0.1-1 mm & ≤ 10 keV*
• 3rd	*Assembled lens made of polycapillaries*	*10 cm & 10-50 mm & ≤ 20 keV*
• 4th	*Monolihic lens made of polycapillaries*	*4-10 cm & 1-10 mm & ≤ 50 keV*
• 5th	*Monolithic integral micro lens*	*1-3 cm & 0.3-1 mm & ≤ 100 keV*

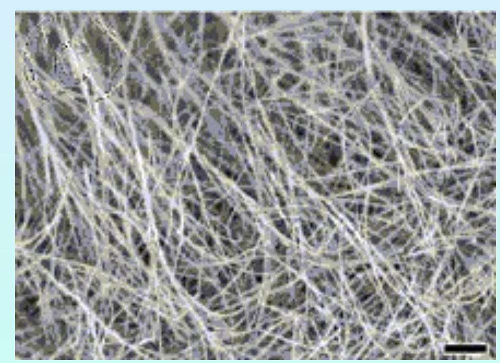
Micro-capillaries

Micro → X-rays

Nano → g-rays (?)

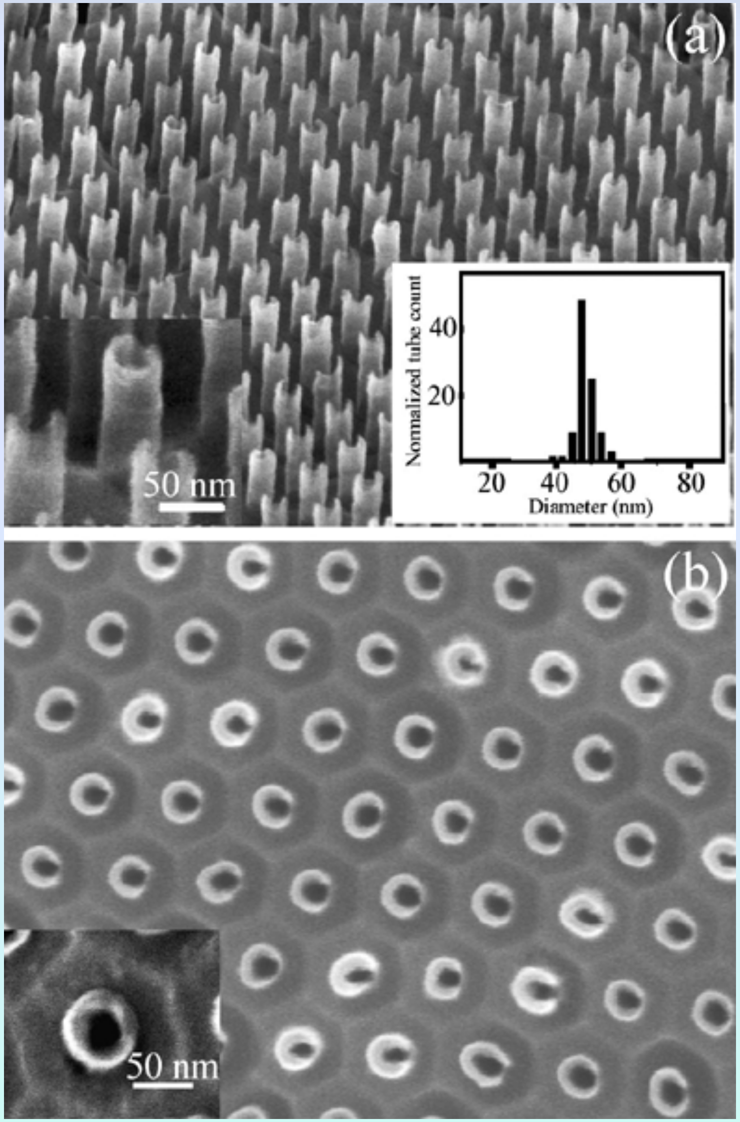


Nanotubes & Nanochannels



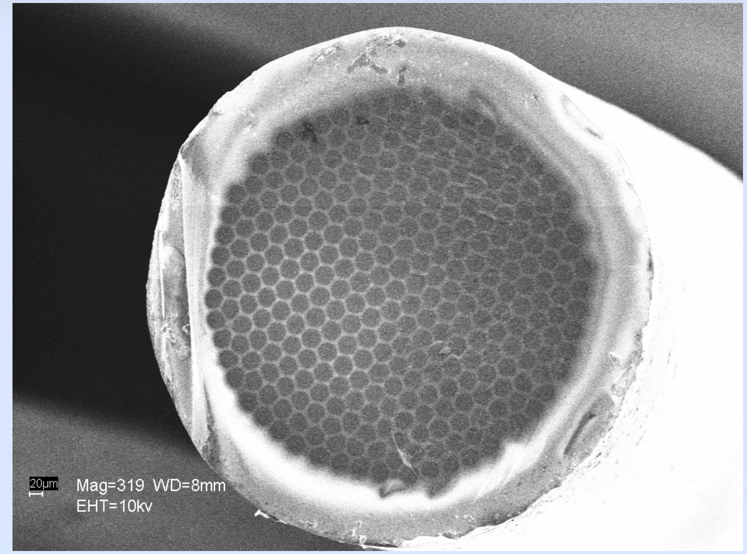
@ Samples of Nanostructures: various openness

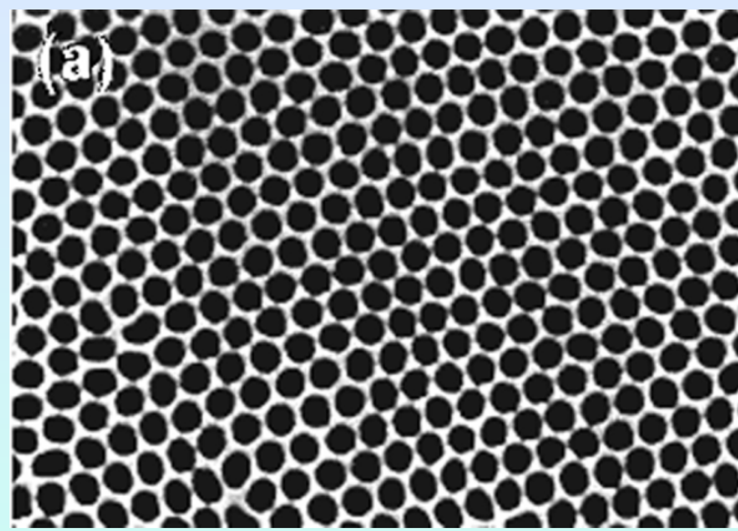
growing



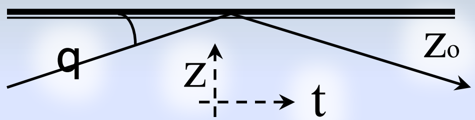
laser burned

polycapillary technology



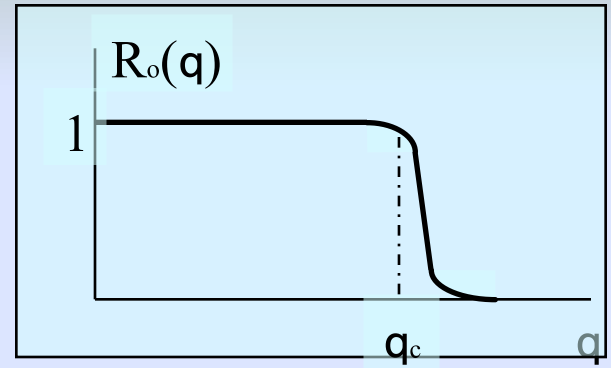


@ basics



$$\Delta \vec{E} + \varepsilon k^2 \vec{E} = 0$$

$$\varepsilon = \begin{cases} 1, & z \le z_0; \\ 1 - \theta_c^{\,2}, & z > z_0 \end{cases}$$



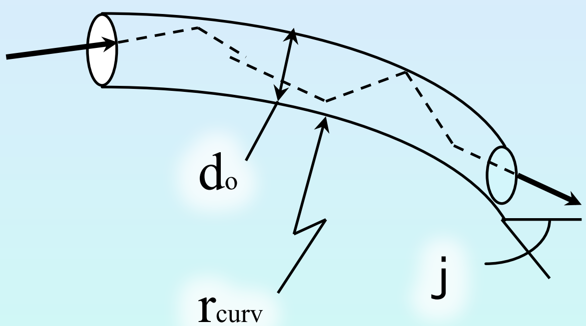
$\theta_c = \omega_p / \omega \approx 30eV/\omega, \quad \omega \rightarrow$ photon energy

$\theta \le \theta_c \Rightarrow$ total external reflection

$\Delta\theta \approx 2\theta_c$

free space

$$I \propto \int_{\theta_{\min}}^{\theta_c} R(x) \sin(x)\, dx \propto L^{-1} \quad \rightarrow L^{-2}$$



$\theta_i \le \theta_c$ - multiple TER

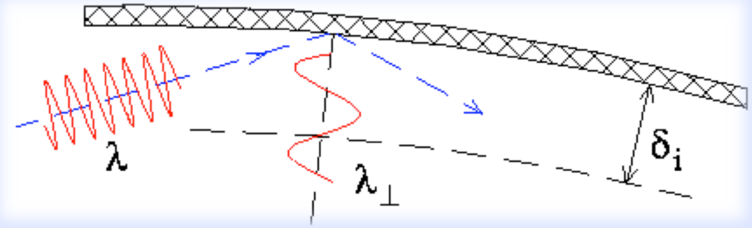
$$\frac{r_{curv}\theta_c^{\,2}}{2d_0} \ge 1$$ - effective guide

$$I(\varphi) \propto \int [R_0(x)]^{N(x,\varphi)} dx$$

@ Modes of channeling along curved surfaces

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

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



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

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

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

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

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

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

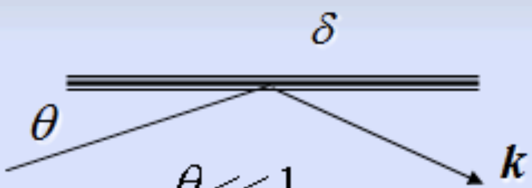
Upper limit of the curvature radius

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

$\lambda \sim 1\ \text{Å}$

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

@ basics of x channeling



$\theta << 1$

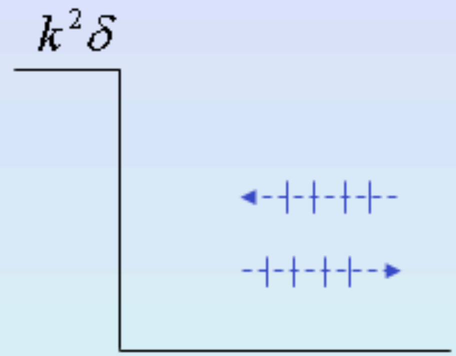
$k_\perp \approx k\theta$

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

Wave equation:

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

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

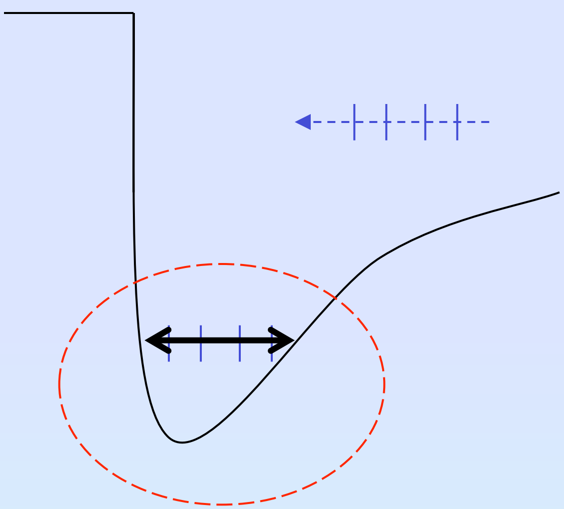


plane (flat) surface

Total external reflection

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

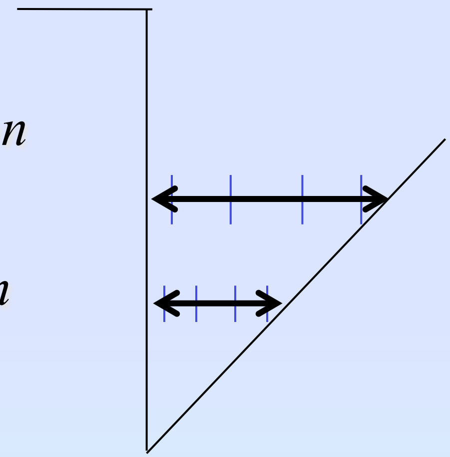
@ basics of x channeling… *Curvature*



approximation

⇨

simplification



additional term to

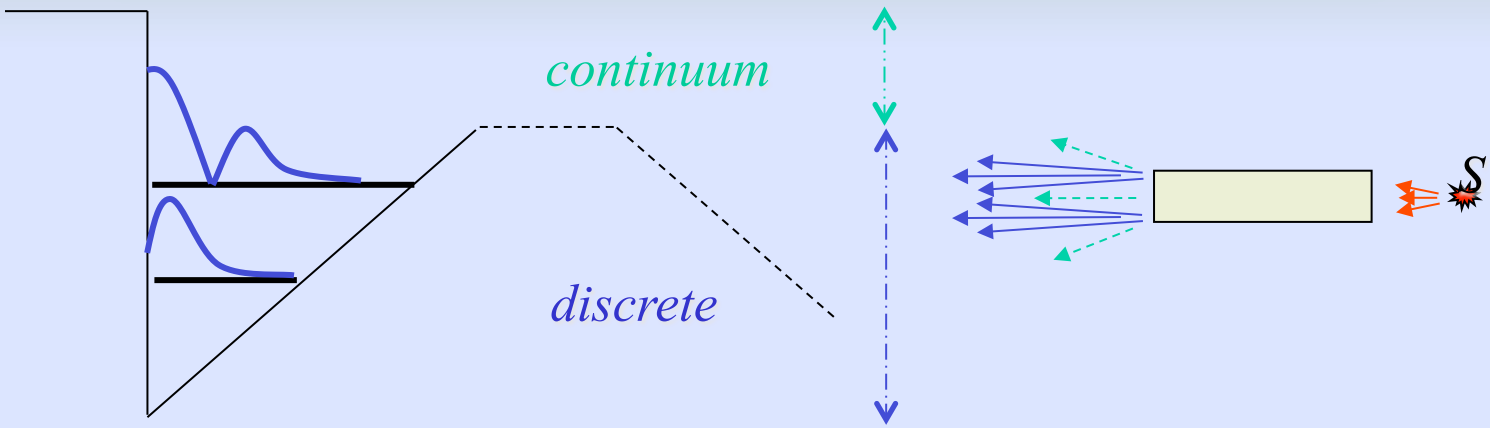
$$V_{eff} \longrightarrow 2\frac{-k^2 r_\perp}{r_{curv}}$$

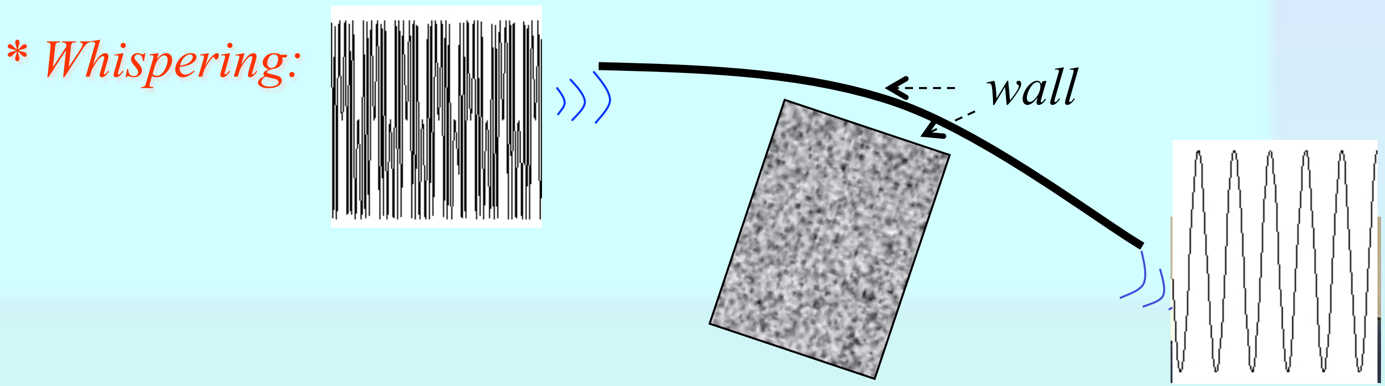
"potential energy":
angular momentum of photon

$$k r_{curv} \varphi$$

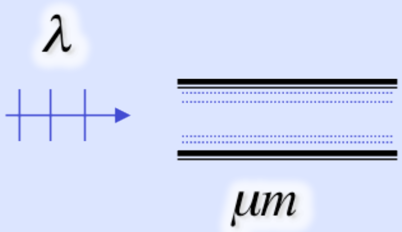
$$V_{eff} = k^2\left(\delta\left(\vec{r}_\perp\right) - \theta^2 - 2\frac{r_\perp}{r_{curv}}\right)$$

@ Surface channeling - "***whispering*** ***X gallery***"





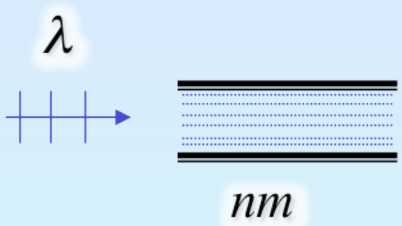
@ Down to bulk X-ray channeling



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

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

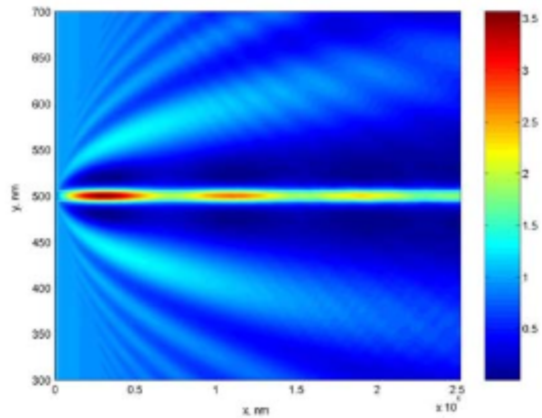
$d_0 \sim 1\mu m \div 10\mu m : \quad \lambda_\perp << d_0$: *surface channeling*



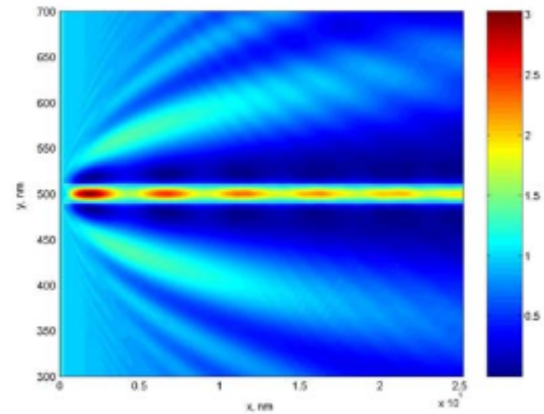
$\theta_d = \lambda / d_0 \sim \theta_c$: *diffraction angle approaches Fresnel angle*

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

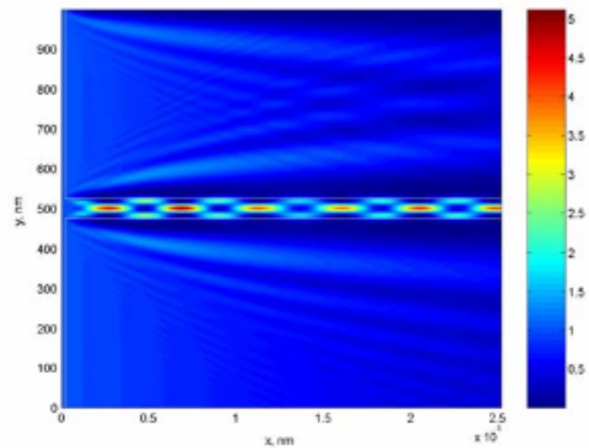
@ Nanocapillaries



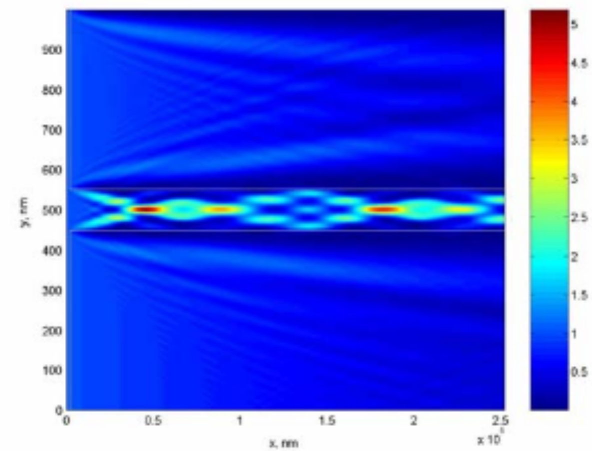
Width 10 nm



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

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

@ polycapillary optics

Basic idea of polycapillary optics is very close to the phenomenon of charged particle channeling

@ deflection by large angles

@ divergent -> convergent

@ divergent -> quasiparallel e vs

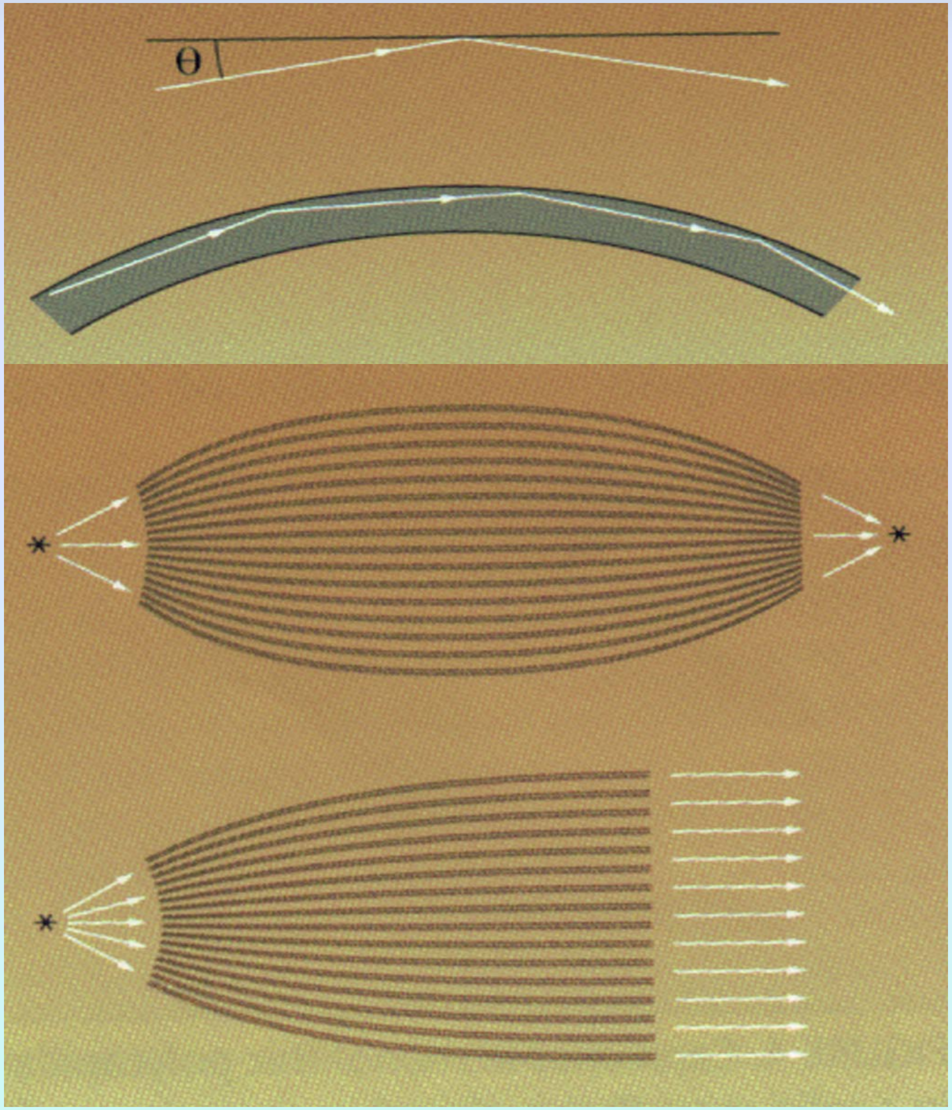
Number of applications

@ scientific instrumentation (XRF, XRD)

@ fluorescence & diffraction

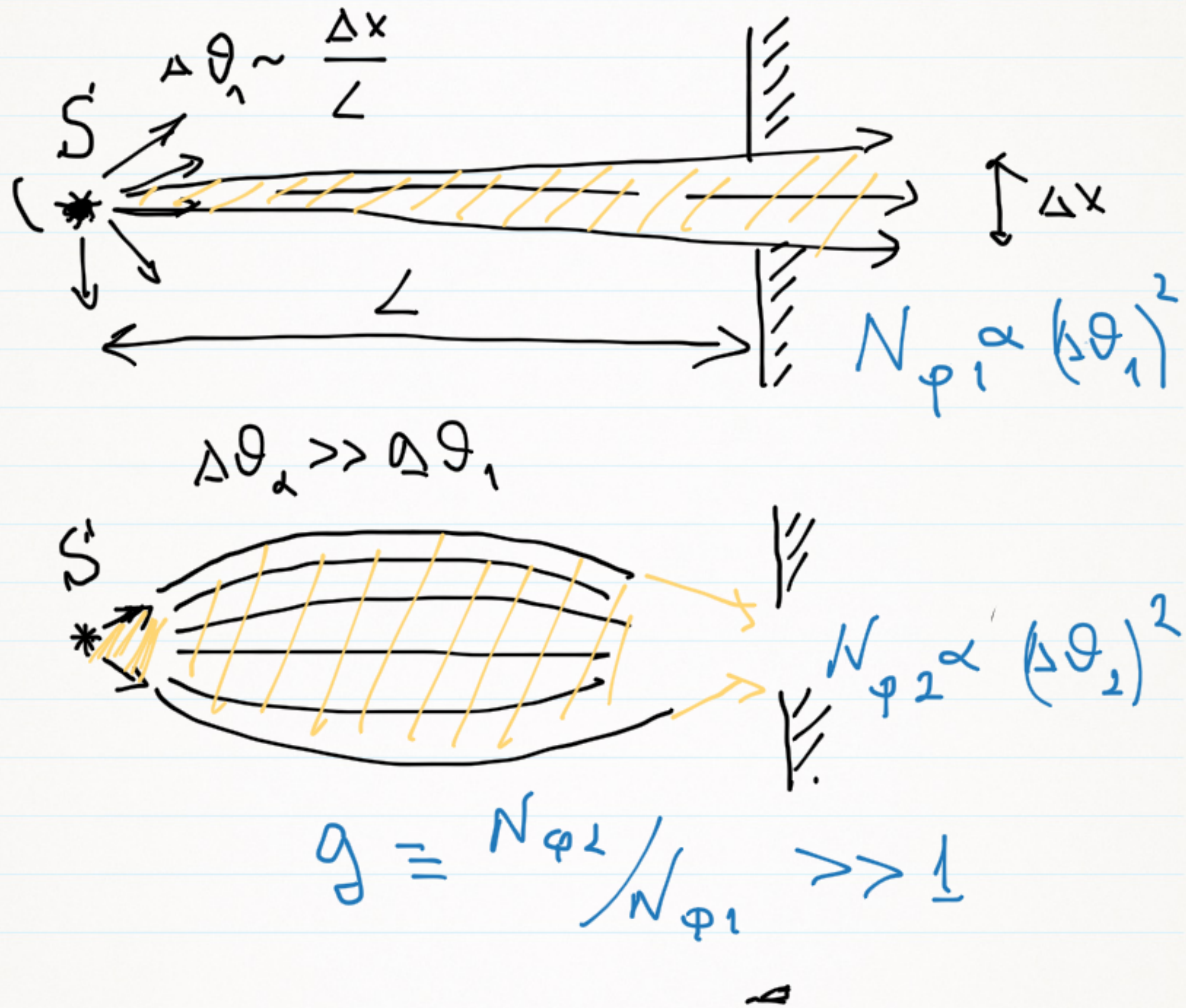
@ medicine (diagnostics & therapy)

@ astrophysics

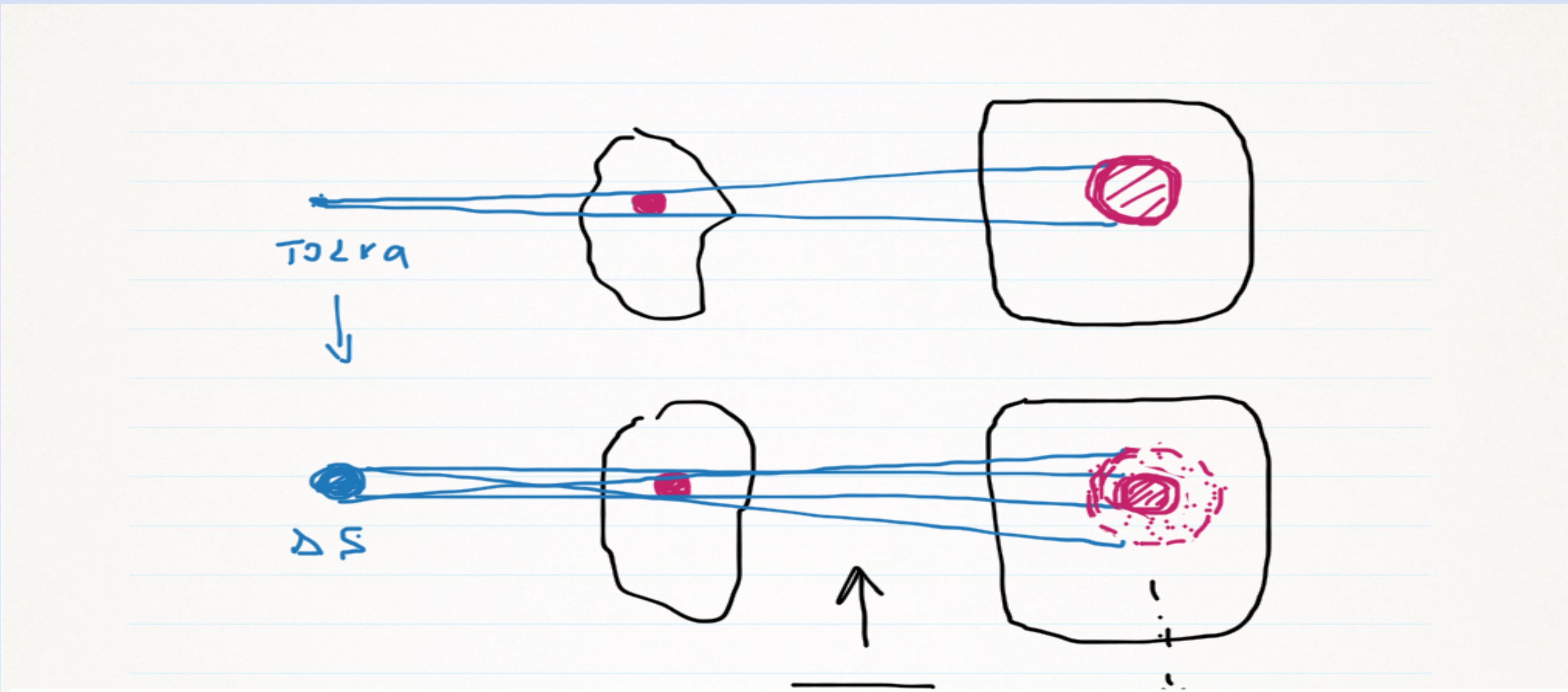


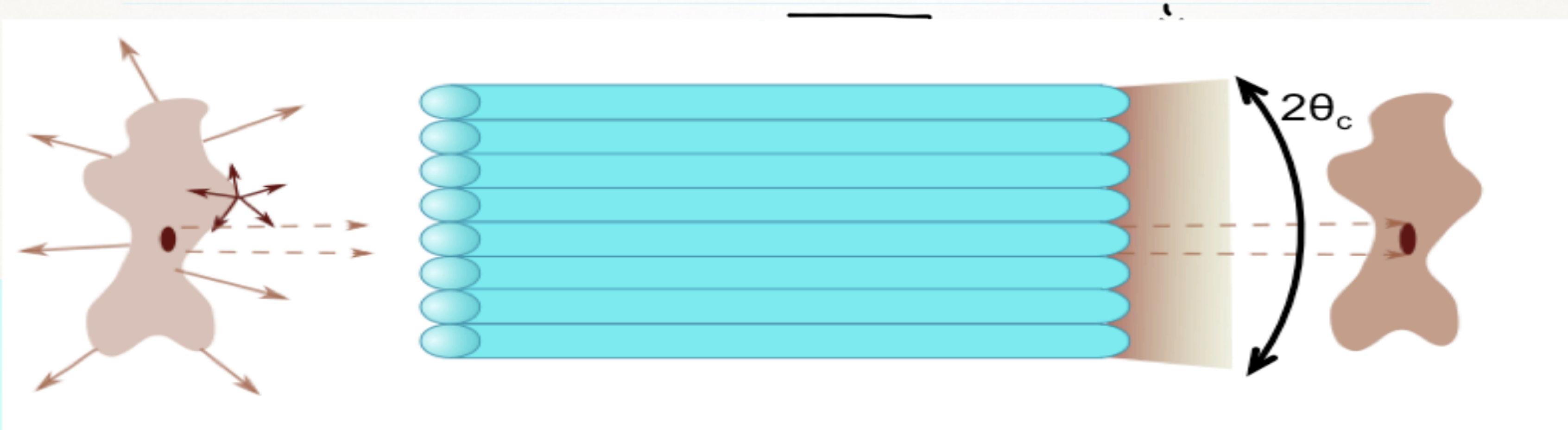
@ two main polyCO options

@ focusing optics



@ collimation optics





@ Divergence - surface channeling

APPLIED PHYSICS LETTERS VOLUME 78, NUMBER 19 7 MAY 2001

Divergence behavior due to surface channeling in capillary optics

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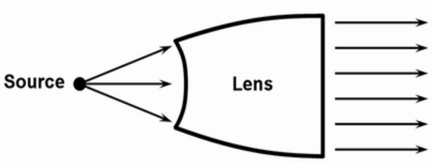
(Received 21 November 2000; accepted for publication 7 March 2001)

Recent studies on the transmitting and focusing properties of capillary optical systems have shown that several unexpected effects take place during the experiments. One such effect is a dec the beam divergence behind the capillary structures. In this letter, we present results c scattering at grazing angles inside capillaries. During x-ray propagation in capillary channe is a strong angular redistribution of the beam, which has been explained in the framewor wave scattering theory. © *2001 American Institute of Physics.* [DOI: 10.1063/1.137011

Today, based on a 10W x-ray tube, developed in-house and combined with optics, we have created an x-ray source producing quasi-parallel monochromatic flux of $10^{10} \sim 10^{11}$ photons/sec•mm^2, which we have used in diffraction studies.



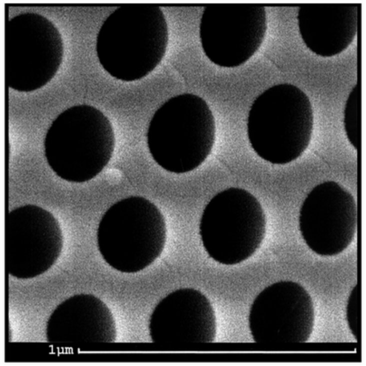
Parallel Beam. Divergence is (2-3)•10^{-3} radian ;
Parallel nature in both directions

Such flux compares well with that usually obtained at synchrotron stations (see Comparison Table 1).

Hence, this system has been named a Laboratory "Synchrotron"

At the same time, in contrast to works carried out at workstations in synchrotron centers where the researchers are strictly limited in time and have other restrains, in our case we provide for a freedom of creativity and possibility of careful and long term investigations.

It should be also taken into consideration that our Laboratory Synchrotron has a reasonable price and is affordable to a great number of scientists, engineers, research laboratories, universities, companies and so on.



Our Laboratory "Synchrotron" is a portable instrument and does not need special premises, or radiation protection measures.

In addition, it can be easily incorporated in existent diffractometers, which is another advantage of our system.

@ PolyCO as a simple Math operator

A polycapillary semi-lens was used to converge radiation into a quasi-parallel beam reducing

Tested in the

rgence of 1.4

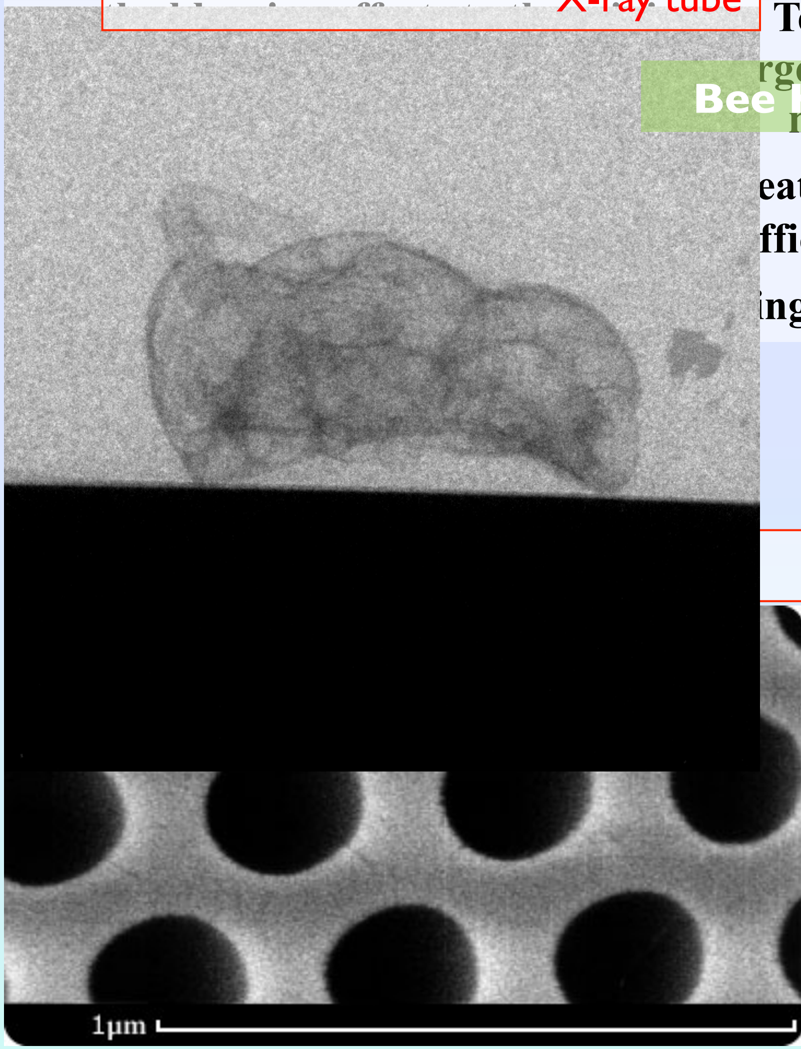
measured.

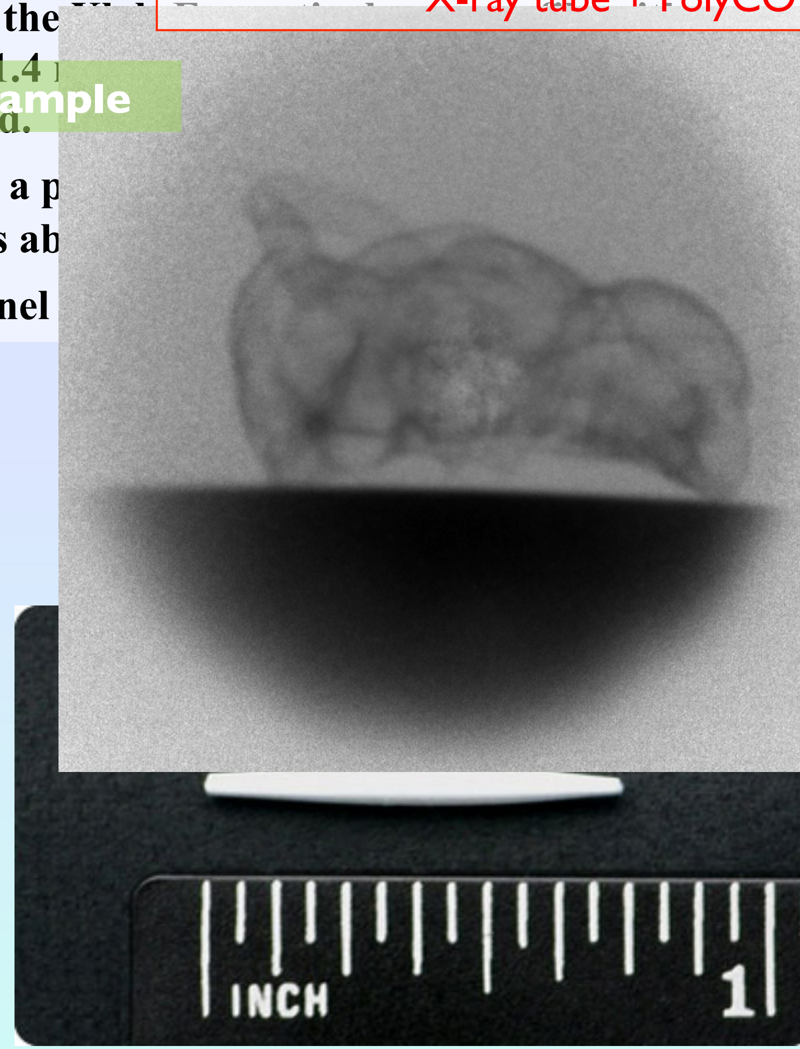
eater than a p

fficiency is ab

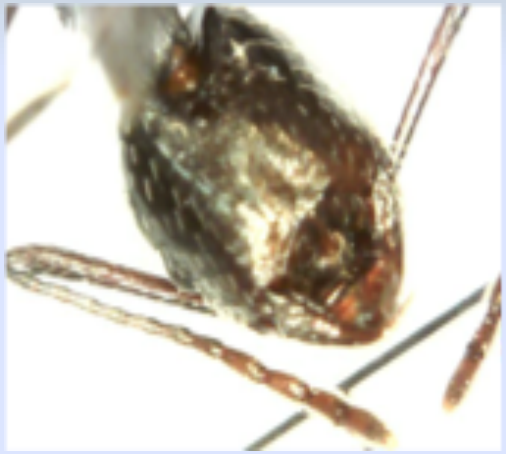
ingle channel

Bee Head Sample



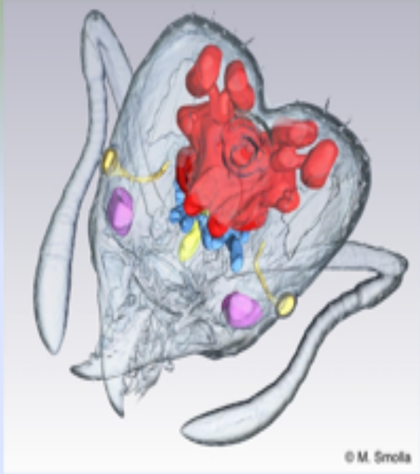


@ PolyCO based μCT: various images

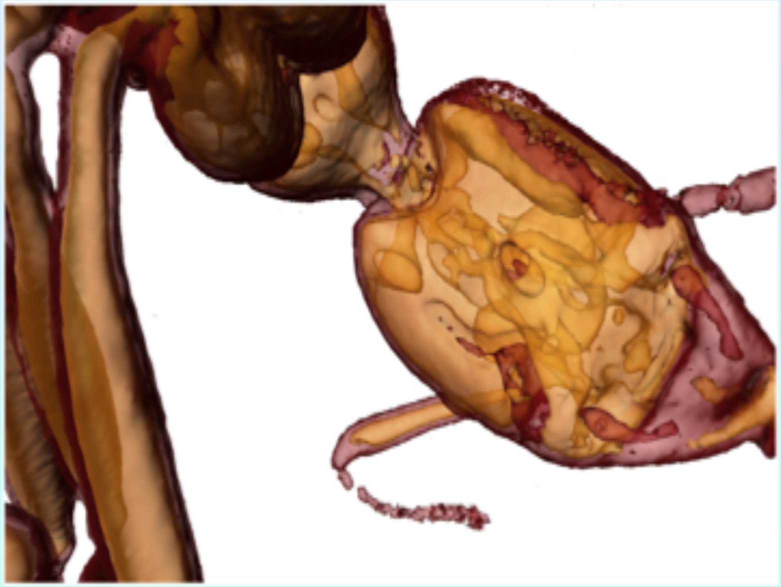


“visible” eyes

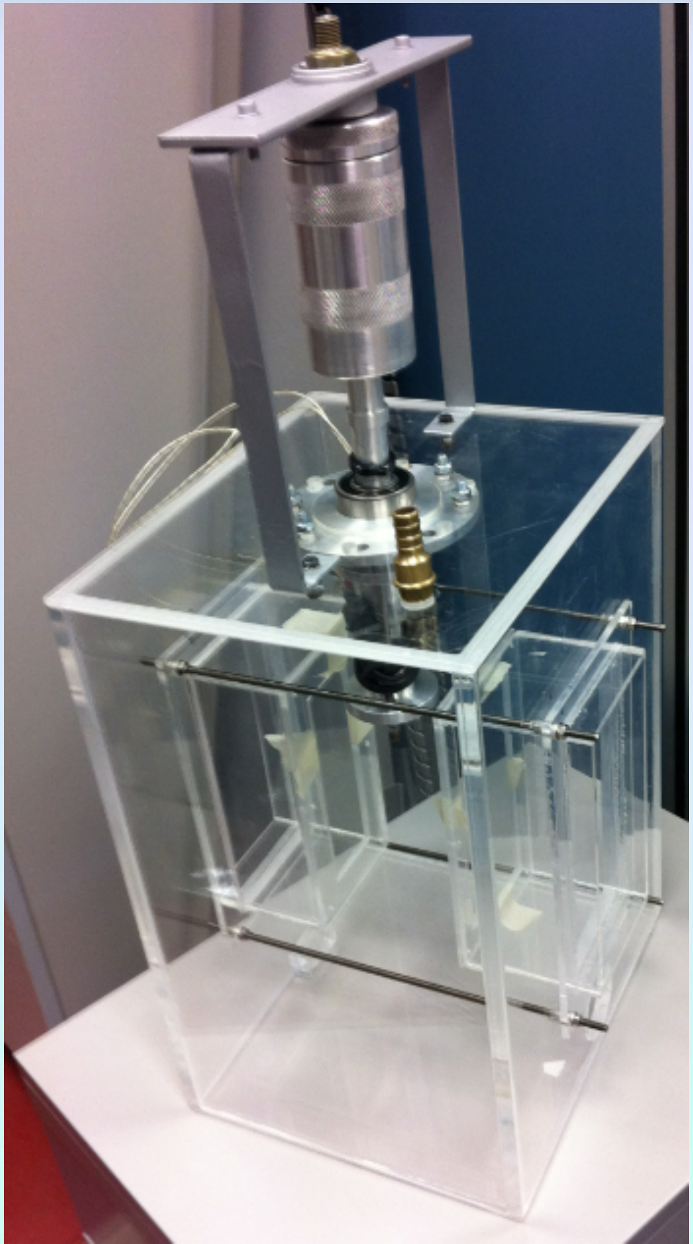
“artist” eyes

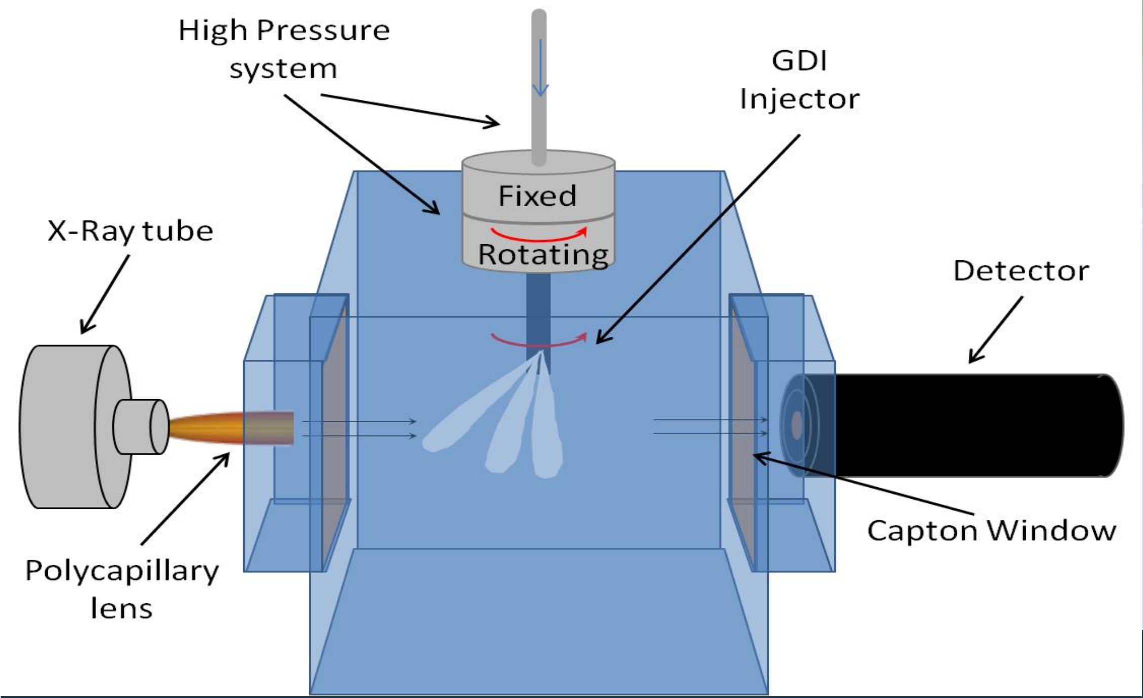


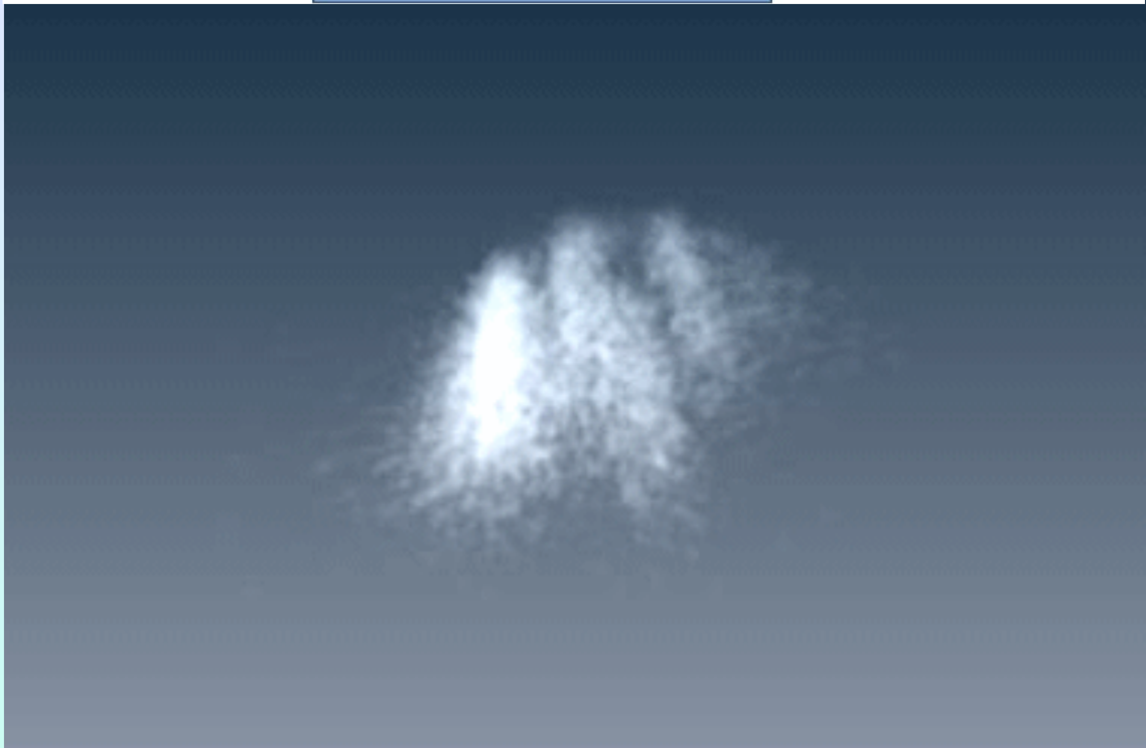
“x-ray polyCO” eyes



@ spray CT

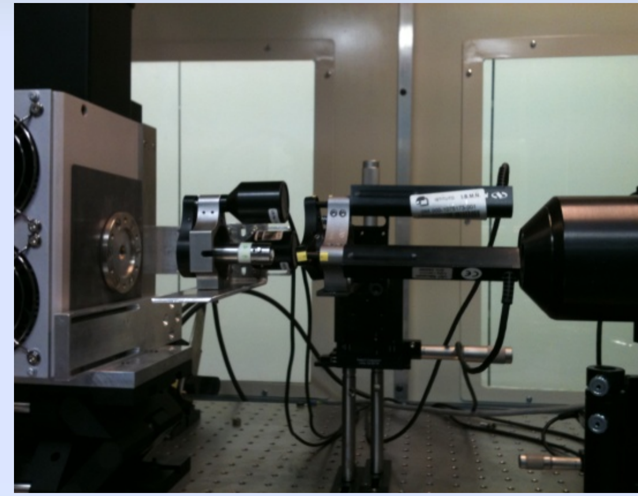



High Pressure
system
GDI
Injector
Fixed
Rotating
X-Ray tube
Detector
Polycapillary
lens
Capton Window



@ X-ray tubes combined with polyCO and CCD/LiF detectors as a compact X-ray imaging facility

X-ray table-top source (XLab Frascati INFN LNF)



The experimental set-up is based on a conventional X-ray tube (Oxford Apogee 5000, Cu target, 50 Watt) **combined with a polycapillary semi-lens.** With the polycapillary semi-lens it is possible to obtain a quasi-parallel beam from a divergence source.

X-ray polycapillary lens and half-lens

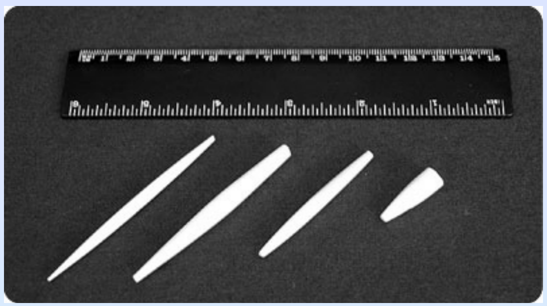
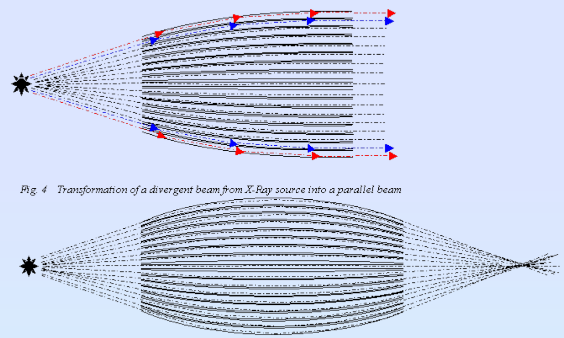
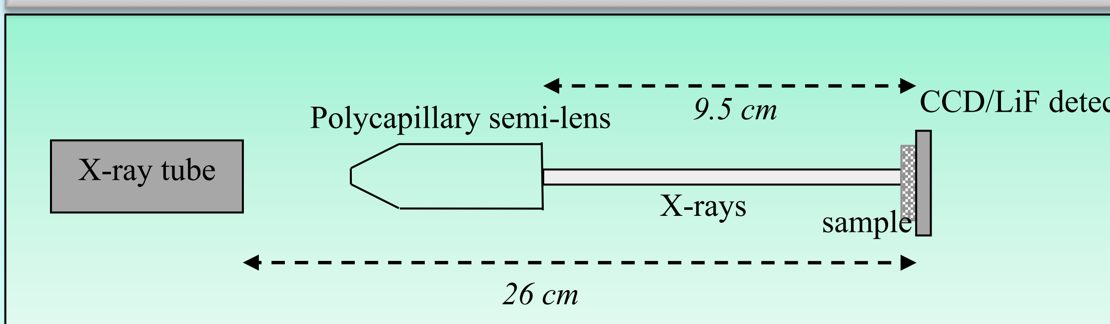


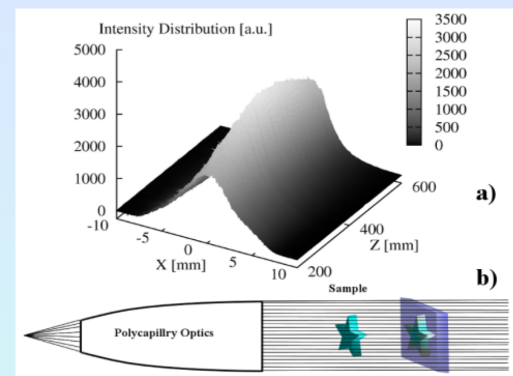
Photo of polycapillary lens and half-lens (http://unisantis.com/



Transformation of a divergent beam from X-ray source into a parallel or a focused beam by a polycapillary lens

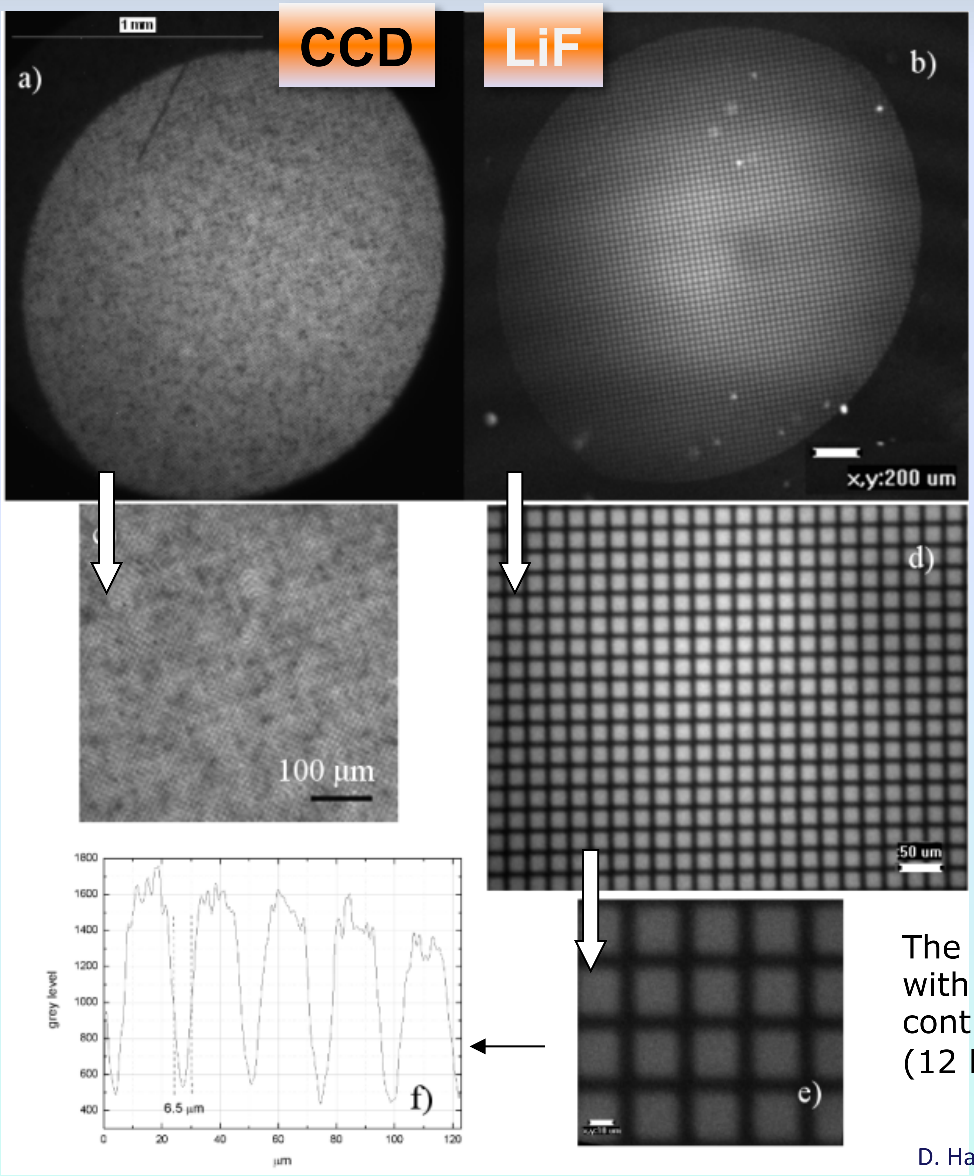
Experimental configuration for contact X-ray micro-radiographies on LiF detectors





a) Measured X-ray intensity distribution contour behind polycapillary half lens
b) Scheme of X-ray imaging with parallel beam produced by a polycapillary optics

@ LiF detectors and X-ray polyCO as a new approach for advanced X-ray imaging



X-ray image of Au mesh 1000 lines/inch (hole width: 19 µm - wire width: 6 µm) acquired by a CCD camera and by a LiF crystal read by a CLSM system.

CCD: Photonic Science - FDI 1.61:1, sensitive area of (4×3)mm^2 and (3.5×3.5) mm^2 pixel size, 12-bit

LiF: crystal (5x5x0.5) mm^3

a, b) X-ray image of Au mesh acquired by a CCD camera and by a LiF crystal, respectively. The fluorescence image acquired by LiF detector, b), was read by the CLSM system.
c), d) Magnified images of CCD and LiF X micro-radiographies, respectively.
f) Magnified image of LiF X micro-radiograph and e) intensity profile along an horizontal line of the luminescent patterned image in LiF of f).

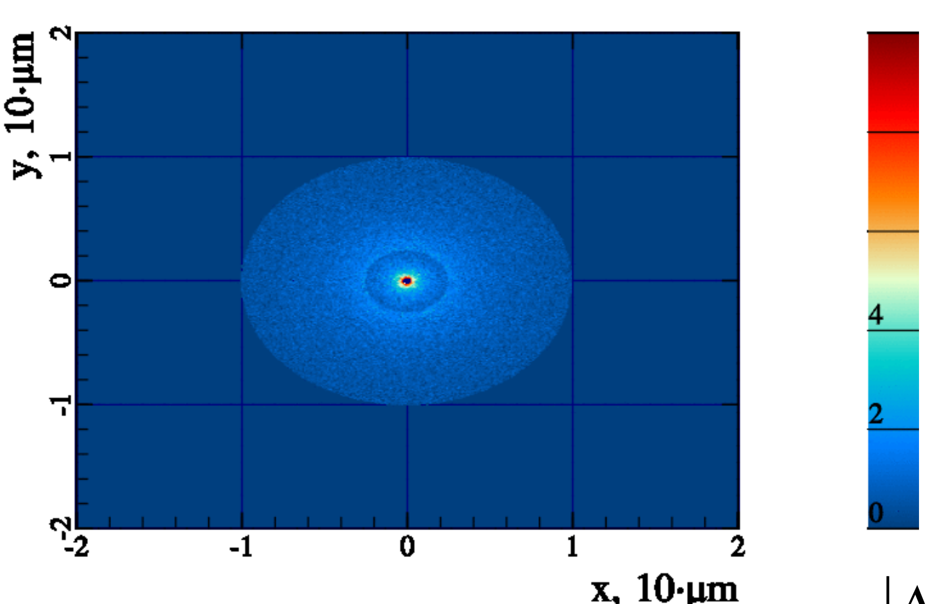
The X-ray micro-radiography stored in the LiF crystal has been read by a CLSM in fluorescence mode

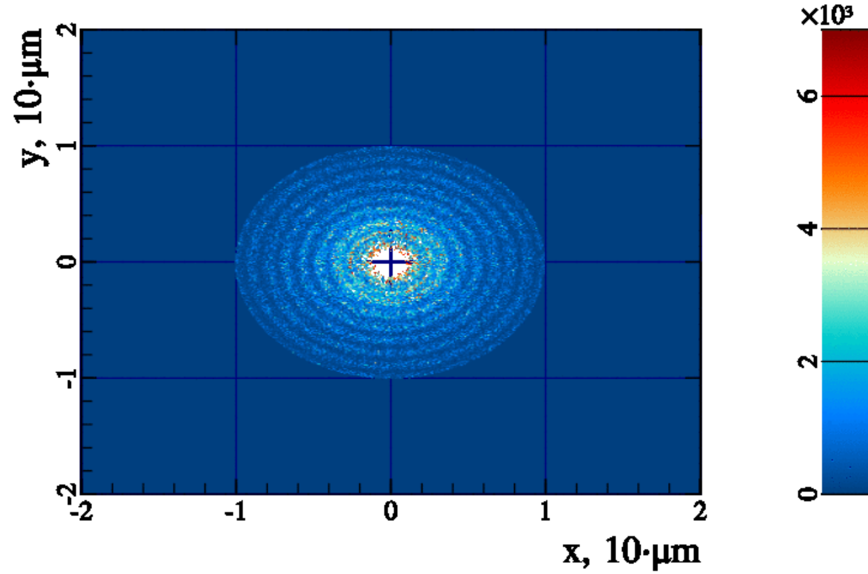
The better quality of X-ray radiography on LiF detector with respect to the CCD one, in terms of resolution and contrast, is evident, although the signal digitalization (12 bits) is the same.

D. Hampai, S.B. Dabagov, G. Della Ventura, F. Bellatreccia, M. Magi, F. Bonfigli and R. M. Montereali, *High Resolution X-ray Imaging by Polycapillary Optics and Lithium Fluoride Detectors Combination*, Europhysics Letters 96 (2011) 60010p1-p4.

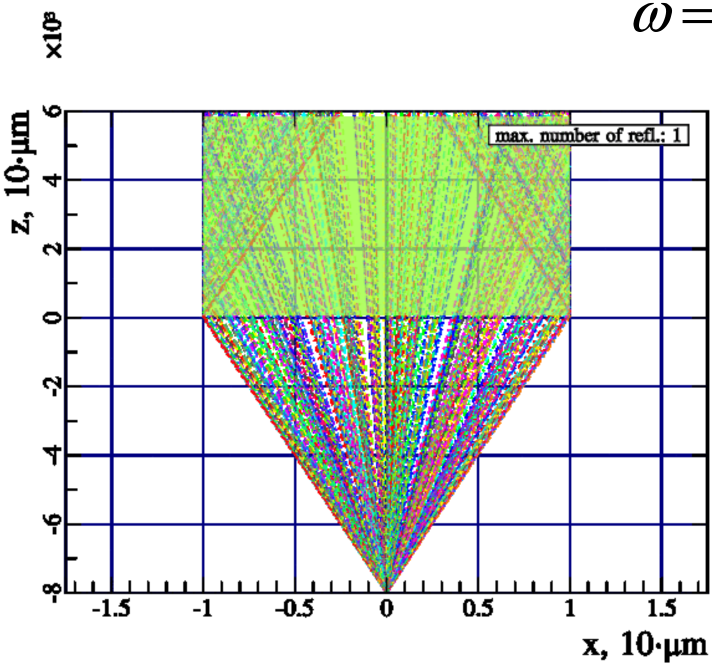
@ new features of X-ray transmission through polyCO

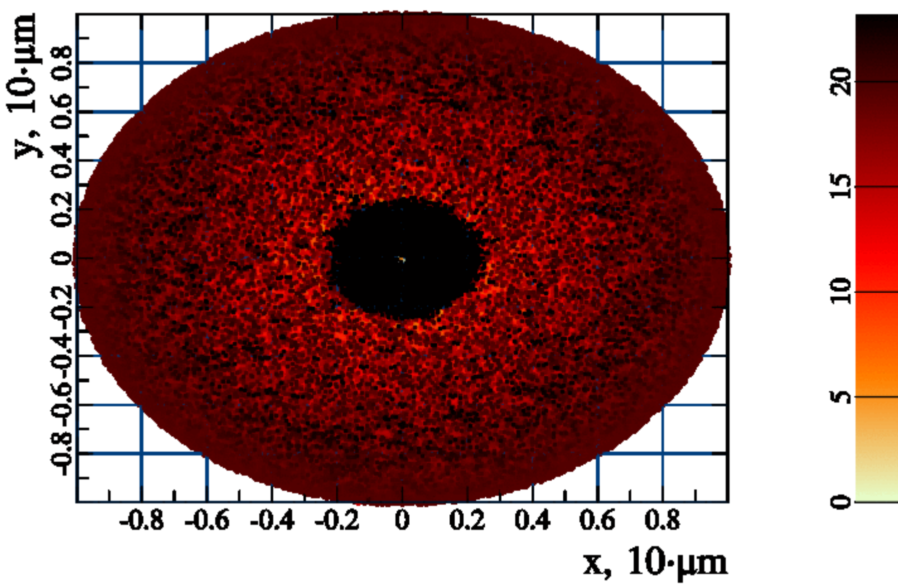
…Coherent & incoherent X-rays behind polyCO samples…

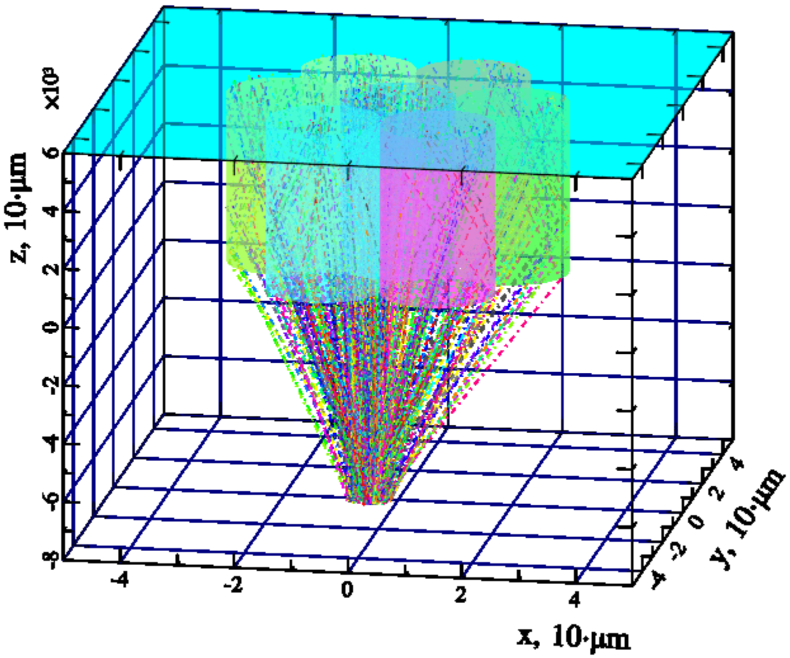


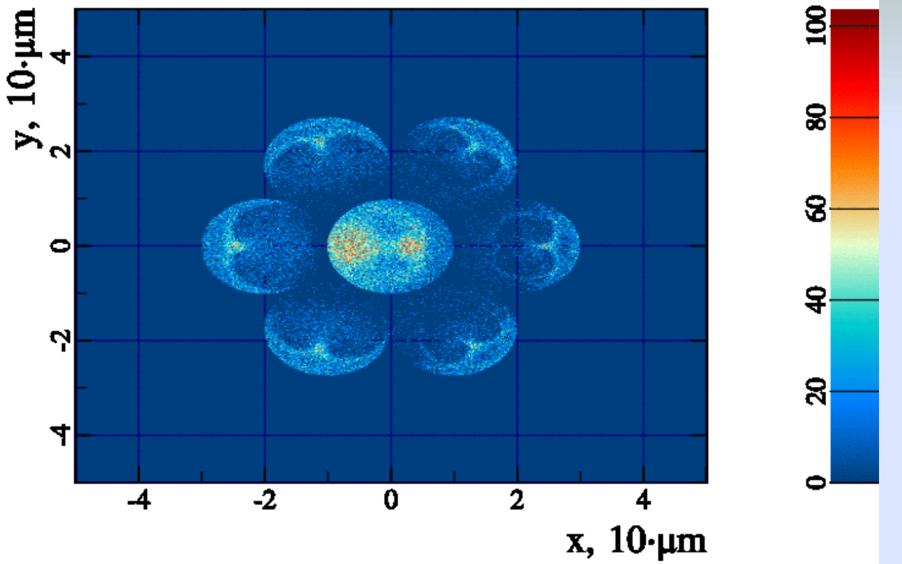


$$\omega = 8\,keV;\ \left|\frac{\Delta\omega}{\omega}\right| = 10\,\%$$









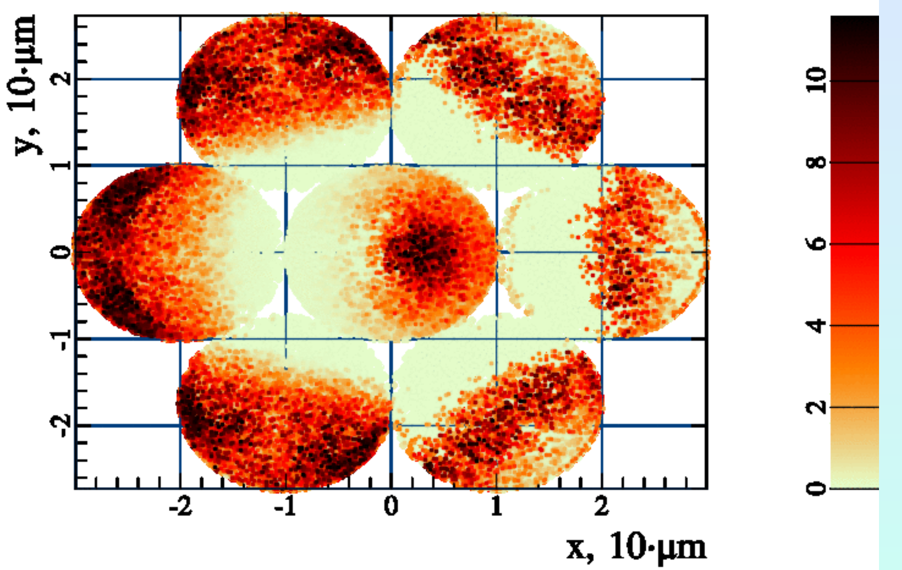
$$\omega = 8\,keV;$$

$$\left|\frac{\Delta\omega}{\omega}\right| = 10\,\%;$$

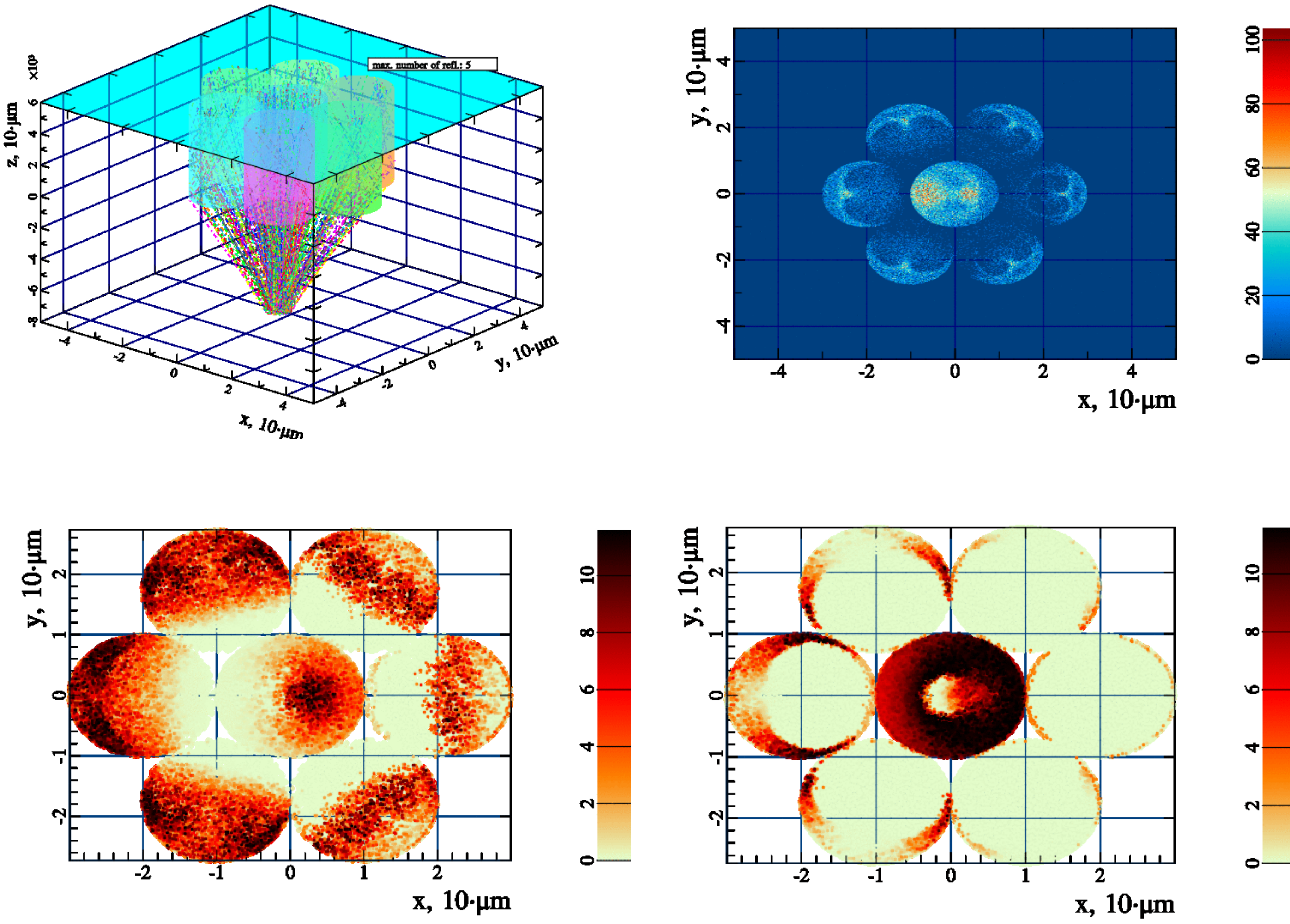
$$d_{sou} = 8\,\mu m$$

$$d_{cap} = 20\,\mu m$$

$$l_{cap} = 6\,cm$$

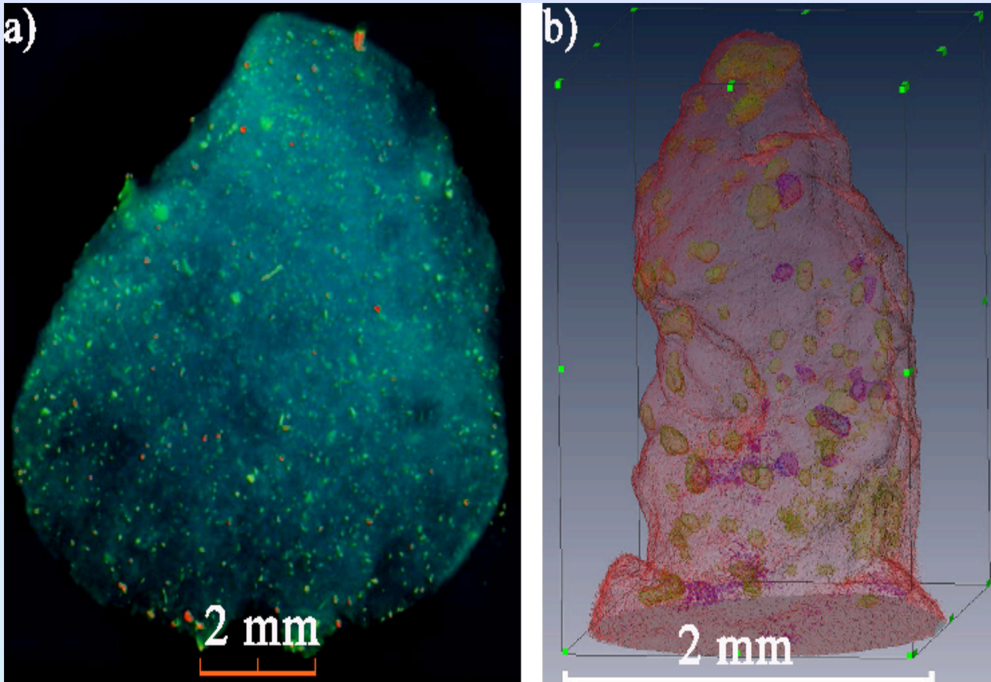


l = 6 cm

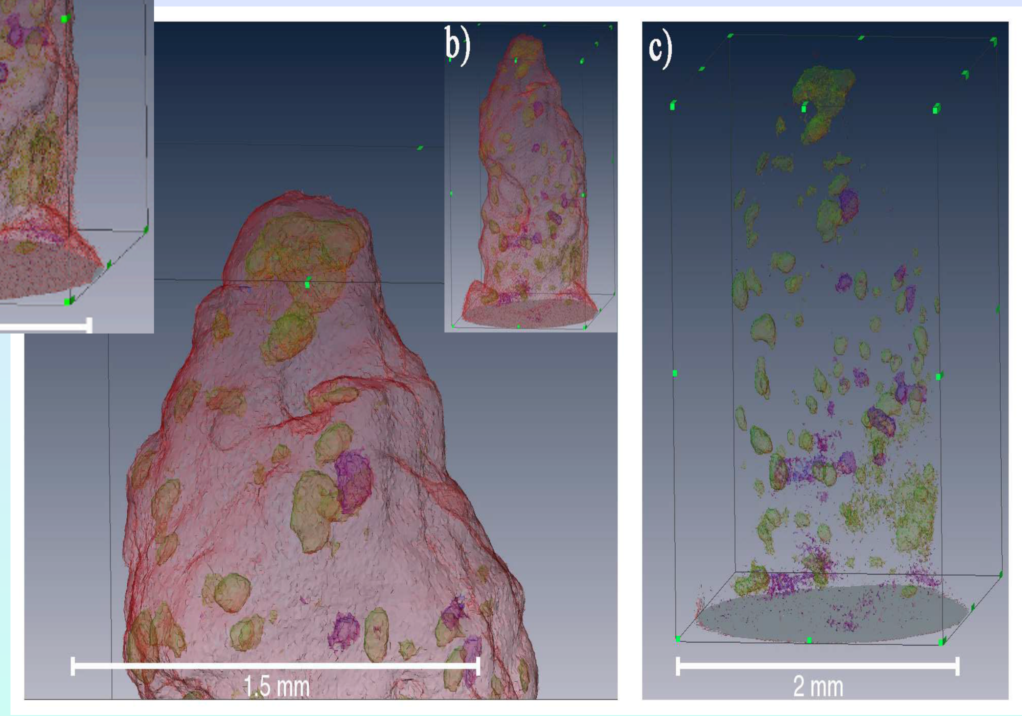

max. number of refl.: 5
z, 10·μm
x, 10·μm
y, 10·μm
×10³
y, 10·μm
x, 10·μm
y, 10·μm
x, 10·μm
y, 10·μm
x, 10·μm

@ studying the porosity based on polyCO matrix

Adobe Sample from Huaca del Sol:
a) Synchrotron Radiation; b) Conventional Source in combination with polycapillary optics



3D reconstruction of the adobe: a) the red area is the adobe, while in b) we want to enhance the different densities areas. Green bubbles represent denser areas, while pink bubbles represent porosities holes.



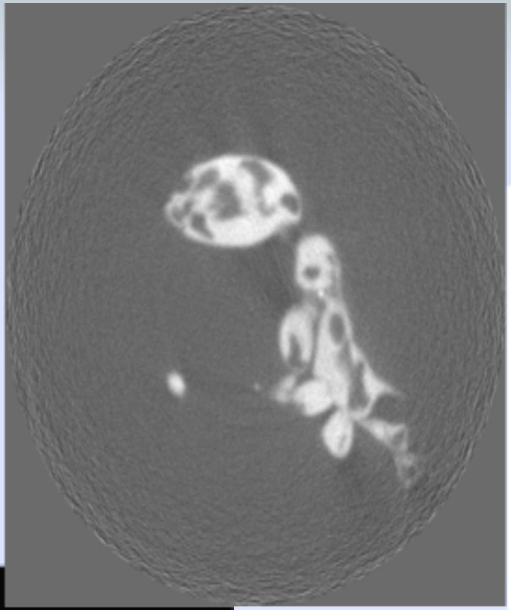
Advanced PolyCO by XLab Frascati

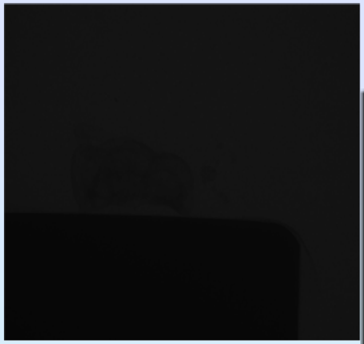
- **X-ray Optics – Polycapillary & Compound Refractive Optics**
- **Material Analisys -- X-ray Spectroscopy:**
  - ✓ **X-ray Fluorescence (normal and total reflection modes)**
  - ✓ **X-ray diffraction**
  - ✓ **X-ray Imaging**
  - ✓ **X-ray Tomography amd micro-Tomography**
- **Diagnostic Applications**
  - ✓ **X-ray Imaging for large objects with high spatial resolution**
- **Crystal Characterization for hadron beam collimation through crystal channeling**
- **Novel technologies and experimental setup**
  - ✓ **Prototype for XRF – TXRF and X-ray Imaging**
  - ✓ **New X-ray tube based on Carbon Nanotube Cold Cathode**

additional

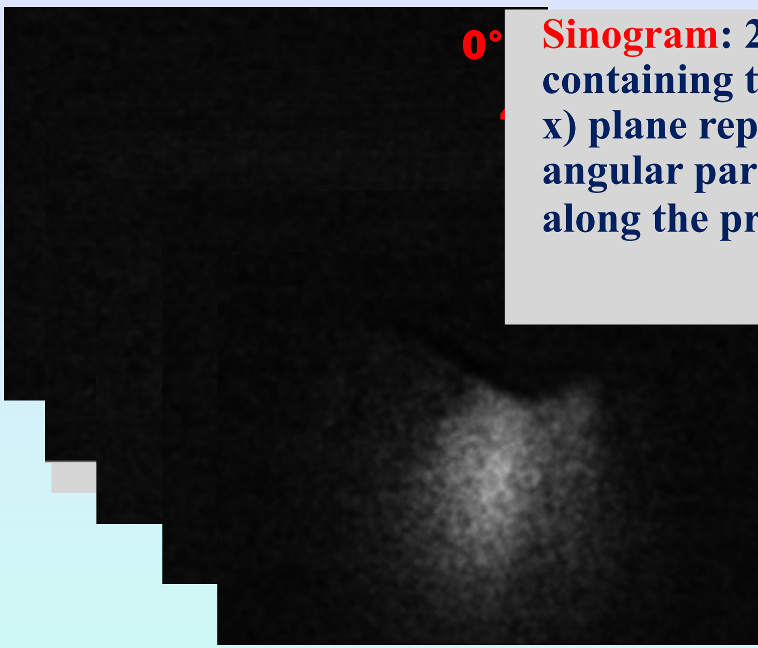
@ PolyCO based μCT

X-ray Tomography of an ant –
- **Polycapillary Semi-lens with 1.4 mrad res. div.**
- Max Power Source 50W;
- Tension: 22 kV;
- Current: 800 μA;
- Exp. Time: 250 ms;
- n° acq.: 720 frames for 360°
- "Octopus" (inCT) and "Amira" Softwares

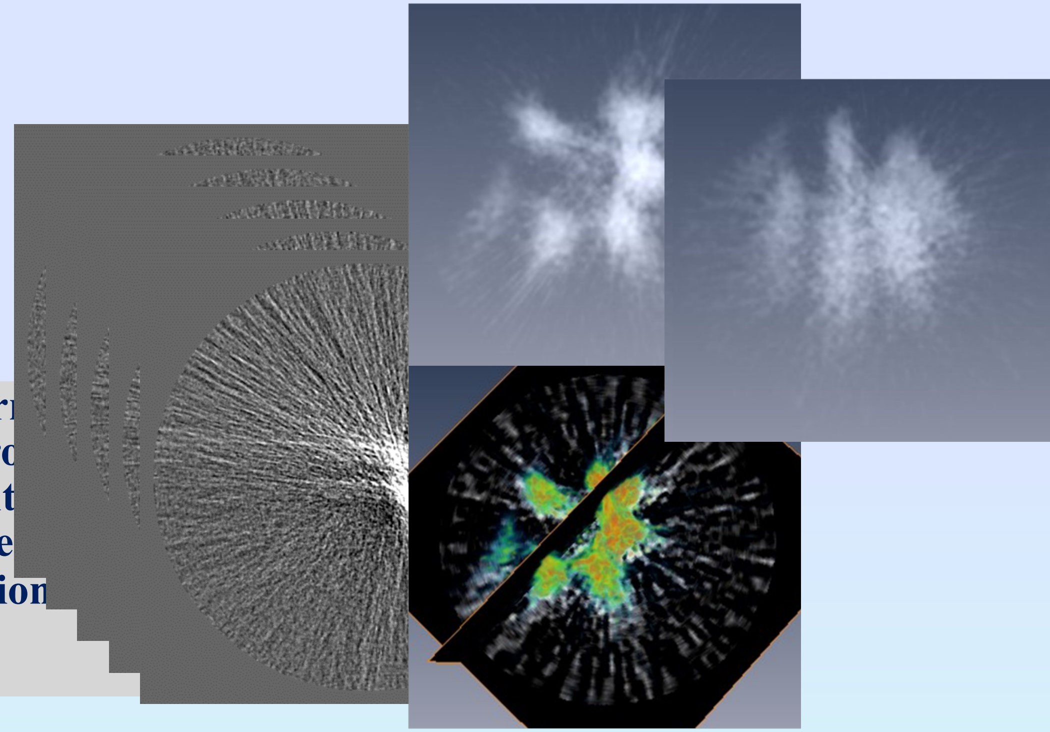




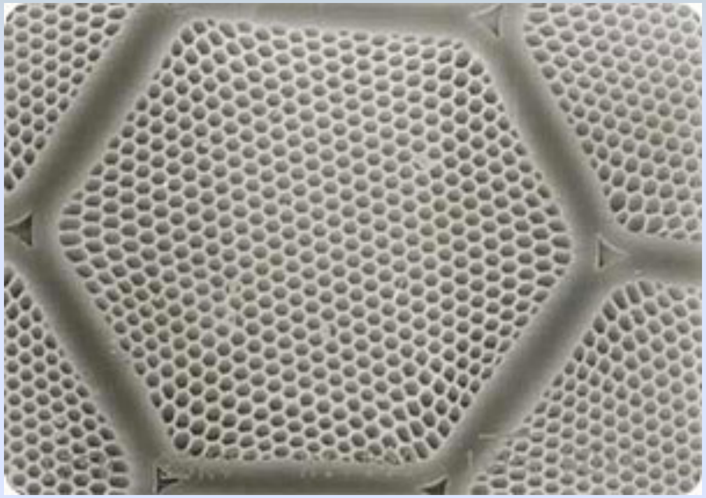
@ spray imaging: basic concept for a fast developing process



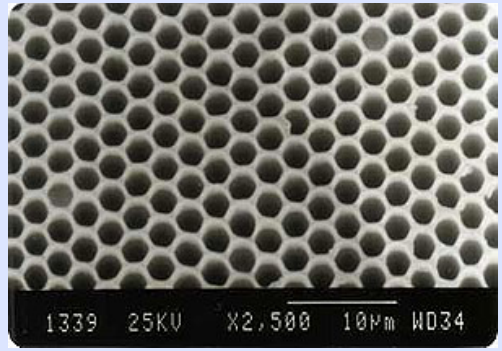
Sinogram: 2-D ar
containing the pro
x) plane represent
angular paramete
along the projection

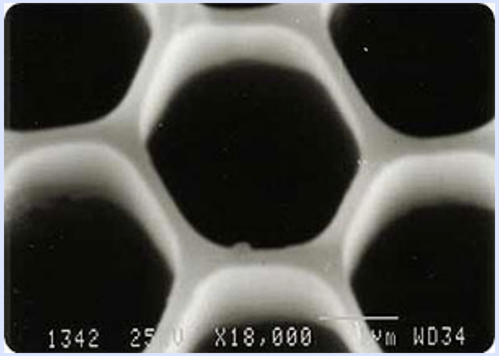


@ characterization of X-ray polyCO with LiF detectors



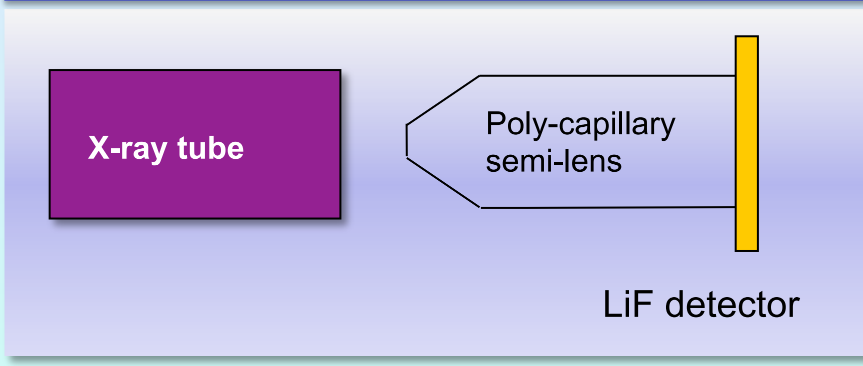
Electron microscope image of polycapillary lens transversal section (http://unisantis.com)

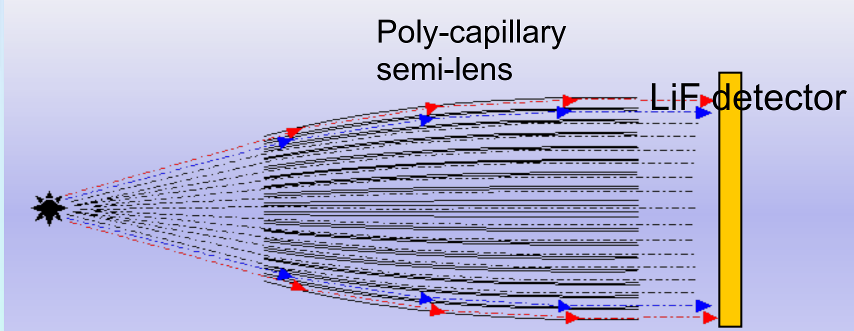




The polycapillary optics is composed by many bundles containing thousands of channels with a length of about 60 mm; each single channel is characterized by an average diameter of about 4 µm.

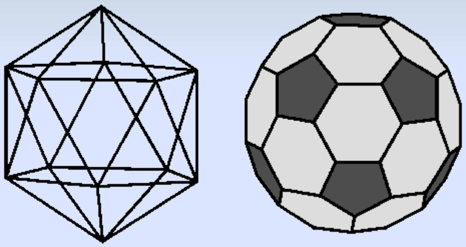
LiF crystal placed at the semi-lens exit





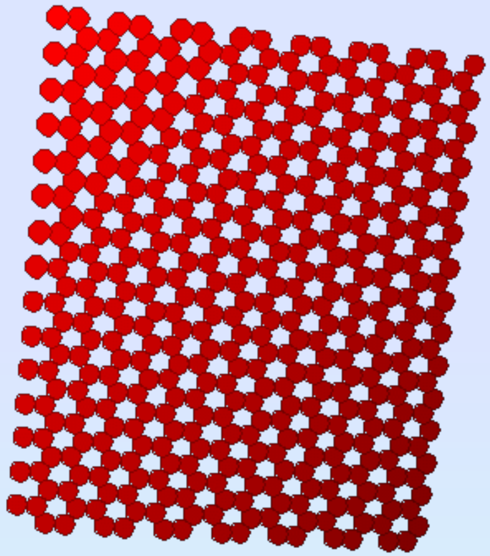
Transformation of a divergent beam from X-ray source into a parallel beam by a polycapillary lens

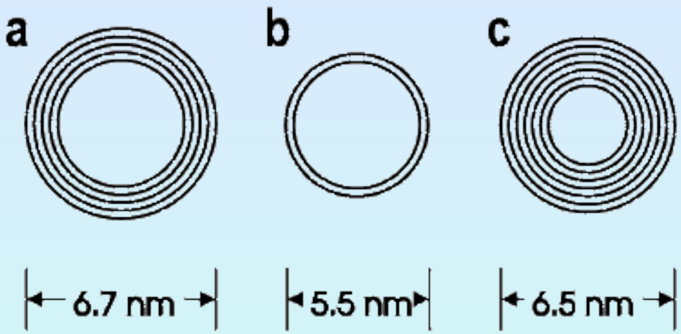
@ Nanotube simulations



Base: *fullerene molecule C_{60}*
sphere of d ~ 0.7 nm

Nanosheet CC

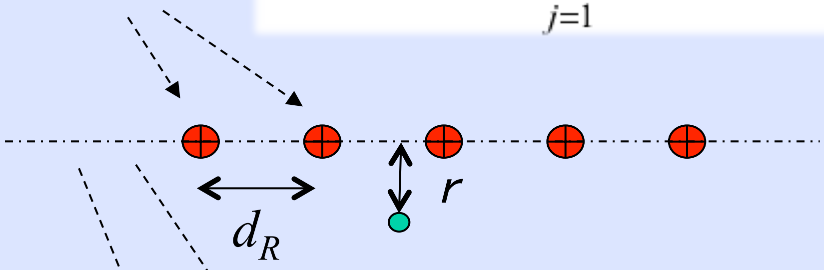




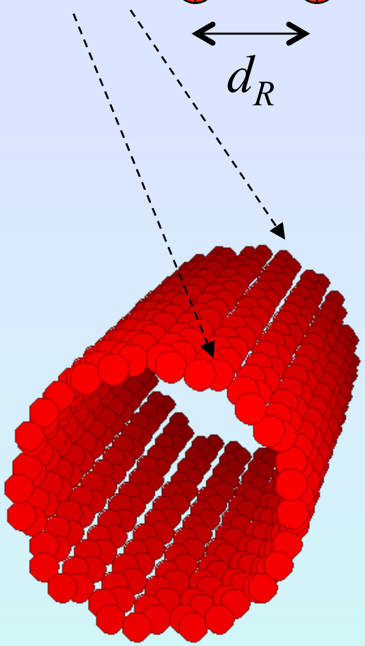
Roled graphite sheets:
nested nanotubes

@ Potentials: Doyle-Turner approximation

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

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

r – distance from the tube

$I_0(x)$ – mod. Bessel function

@ Potential for neutral particles: Moliere approximation

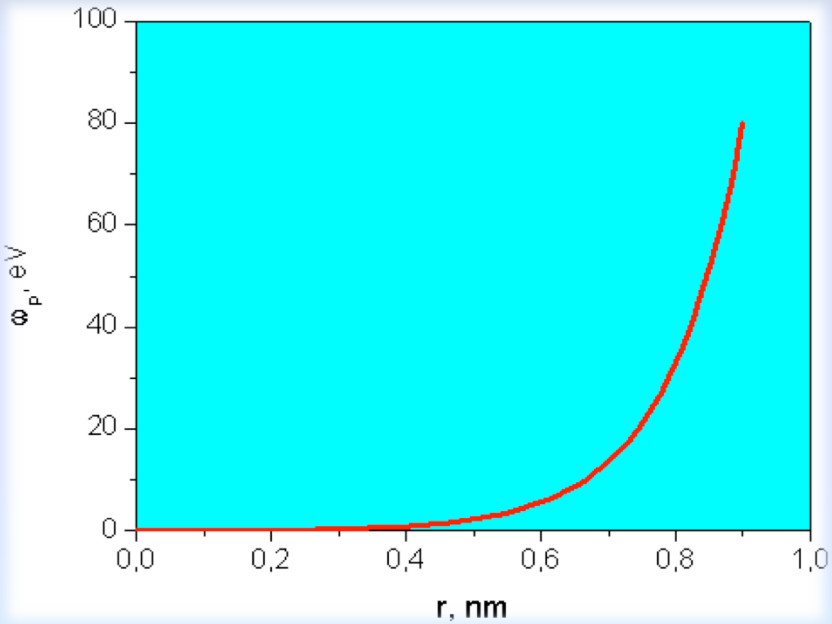
$$N_e(r) = \frac{Z}{4\pi a^2 r}\sum_{i=1}^{3}\alpha_i \beta_i^{\ 2}\exp\left(-\frac{\beta_i r}{a}\right)$$

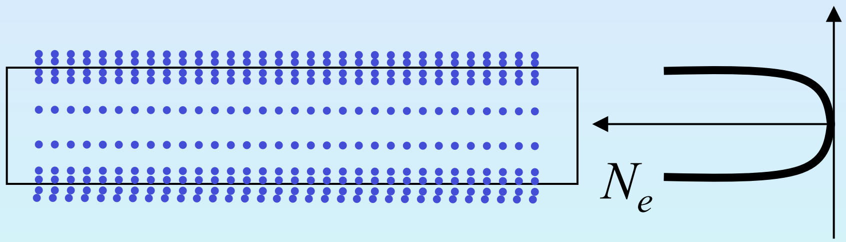
$$C: \qquad Z = 6$$

$$a \approx 0.05 Z^{-1/3} - \quad screening \quad length$$

$$\overline{N}_e(r) \approx \frac{r_{curv} n_a Z}{\pi a^2}\sum_i \alpha_i \beta_i^{\ 2}\int_0^{\pi} d\theta K_0\left(\frac{\beta_i \rho}{a}\right)$$

$$\rho = \left(r^2 + r_{curv}^{\ \ 2} - 2 r r_{curv}\cos\theta\right)^{1/2}$$

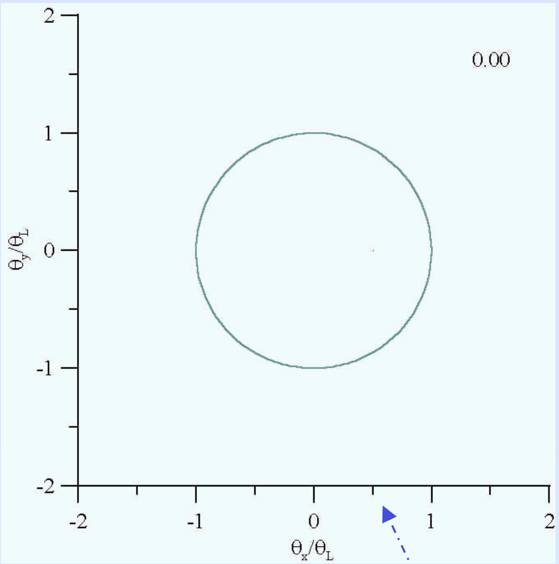


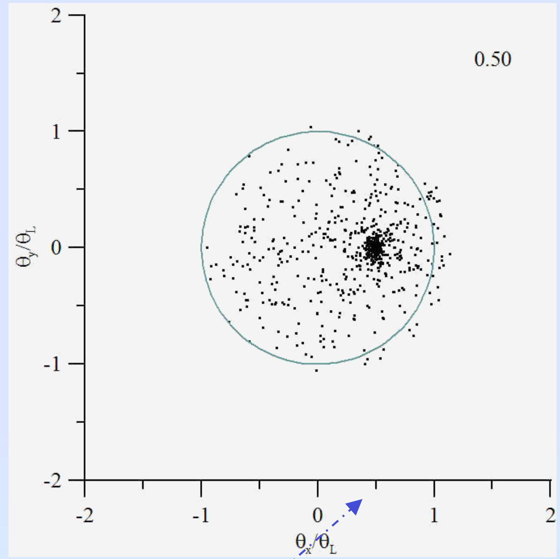


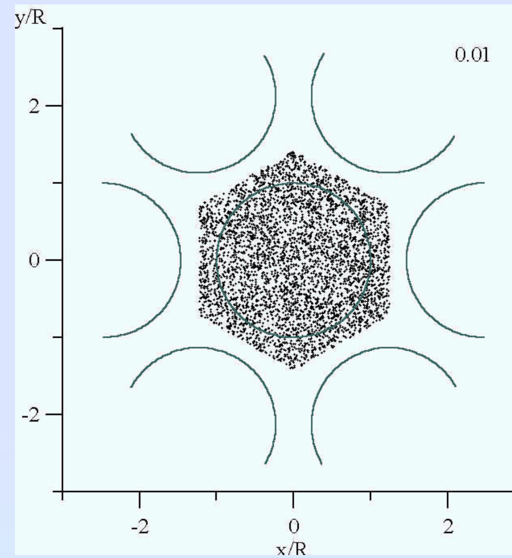
"Continuous filtration by energy"

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

Angular distributions *Spatial*





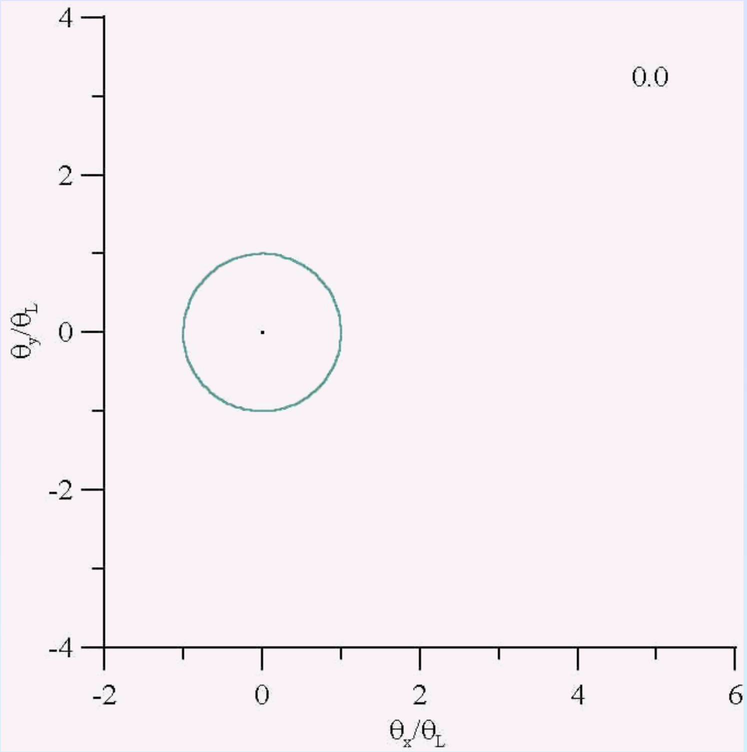


Coherent scattering:
0-L_0

Multiple reflections:
L_0-$20L_0$-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