elettra Synchrotron Light Laboratory

μXFA beamline and multilayer laboratory

Multilayers and microscopy optics

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http://www.elettra.trieste.it/experiments/beamlines/microfluo/index.html

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In memory of J.C. Fuggle and L. Fonda, Trieste, 11/05/2006

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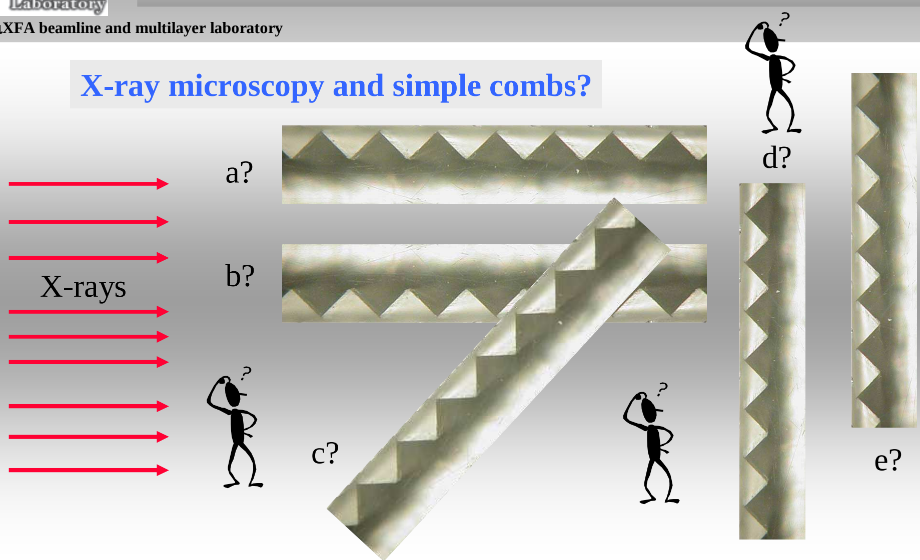
X-ray microscopy

X-ray microscopy and simple combs?



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Structure of lecture

- possible objectives for x-ray microscopy
- ultimate resolution limit
(more in two weeks: applications)

Which phenomena to use
- reflection
- diffraction
- refraction

W.C. Roentgen: There are no refractive lenses for x-rays!

- combinations

Note: This presentation is neither historically correct as a whole nor complete for the single items.
It is limited to (often newer) experiments, which can explain the concepts in the most instructive way.

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Why microscopy with SR?

A) use unconventional contrast mechanisms

– absorption edges (e.g. in water window)
– dichroic response (helicity)
– others, hopefully you invent them at this school

B) in visible: spatial resolution ≈ light wavelength

will shorter x-rays reveal the yet unseen atoms?

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Why x-ray microscopy?

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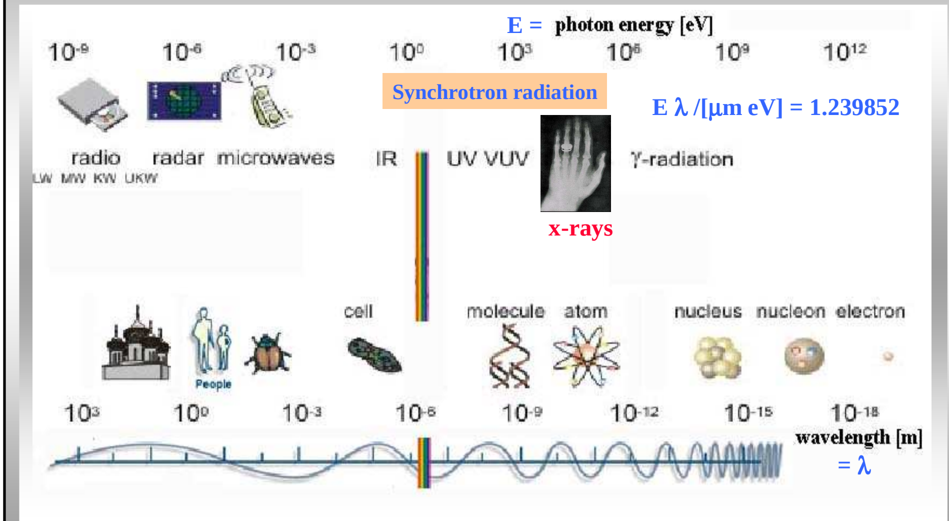

Why x-ray microscopy?

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Very lively discussion just started:

What is the ultimately possible spatial resolution?

Please note:

we are here concerned with the smallest size into which we can confine x-rays!

X-ray crystallography instead reveals structures with very high spatial resolution, however, only of crystalline samples. “Lensless” or coherent x-ray diffraction imaging of intrinsically noncristalline objects promises high resolution (see elsewhere).

Microscope objectives for visible

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A) Magnifying lens

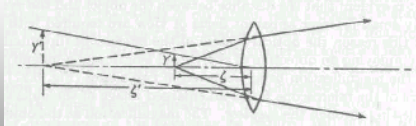


Fig. 6.26. The magnifier.

B) Microscope

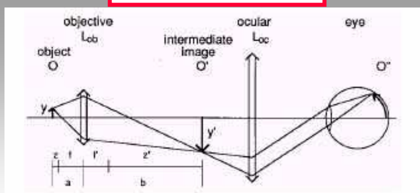


FIGURE 3 Ray path in the microscope from object to observer's eye (see text).

C) Schwarzschild objective

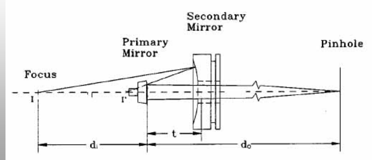
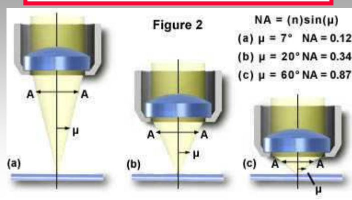


FIG. 1. SO geometry and image formation.

D) numerical aperture



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Similarities

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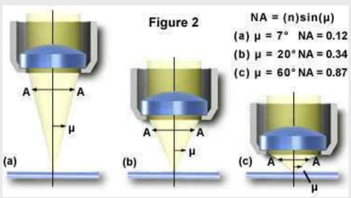
The resolution of a microscope is given by

$R = \lambda/(2NA)$ NA = numerical aperture

Note: depth of focus $\Delta f = R/(2NA) = \lambda/(2NA)^2$



MAXIMISE in any case NA

with refraction, reflection or diffraction

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Characteristics of x-rays

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- wavelength: ca. λ=0.06 nm (E=20 keV)
- negligible absorption in air
- large variation of absorption in material
- reflected with surface mirrors only at grazing incidence Φ
  (rule of thumb for Pt coating: E*Φ/[keV*mrad] = 80)
- reflected/monochromatised at lattice planes of highly regular crystal structures

Softer x-rays with 0.6 nm < λ < 30 nm (40 eV < E < 2 keV)

- significant absorption in air (vacuum required) and material
- mirrors for reflection
  gratings for monochromatisation

What about the comb?

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Some basic properties

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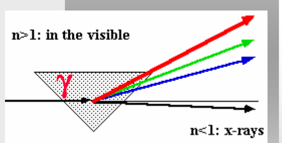
- refractive index $n = 1 - \delta + i\beta$,
  where i=sqrt(-1) and $\delta, \beta \ll 1$

$$\delta = \frac{r_e \lambda^2 N_e f_1}{2\pi}$$

r_e = 2.8 10^{-13} m, N_e = no. atoms/unit volume
f_1 = tabulated atomic scattering factor (e.g. www-cxro.lbl.gov)

- in x-ray range: $\delta \propto \lambda^2$ $\beta \propto \lambda^4$
- total reflection angle $\Phi = \mathrm{sqrt}(2\delta)$
- deflection in a prism $\Delta = -2\delta/\tan(\gamma)$
- phase retardation $\Delta\psi = 2\pi l\delta/\lambda \propto \lambda$
- absorption $\mu \propto \lambda^3$



e.g. for plexiglass at λ=0.154 nm (8.05 keV): δ = 4.2 10^{-6} $1/\mu \approx$ 1.3 mm
then Φ = 2.9 mrad (0.167°) $\Delta(\gamma=45°)$ = -8.4 µrad (1.7")
l =36.67 µm provide 2π phase shift

What now about the comb?

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Comb x-ray lens: Do-It-Yourself!

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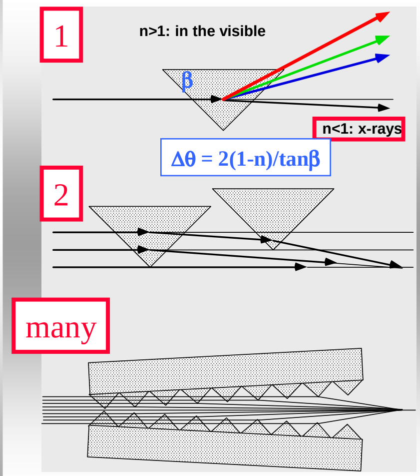
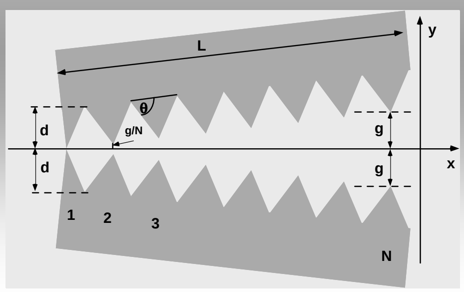


B. Cederström, R. N. Cahn, M. Danielsson, M. Lundqvist, D. R. Nygren:
Focusing x-rays with old LP's
Nature 404, 951 (2000)



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X-ray microscope schemes

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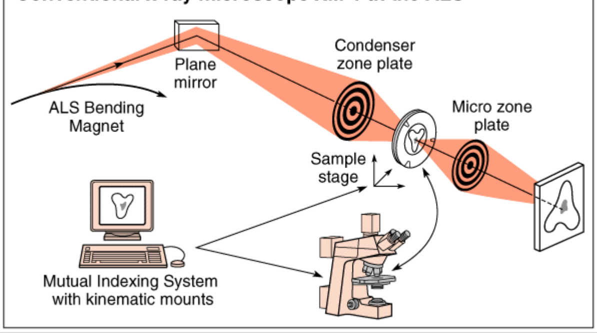
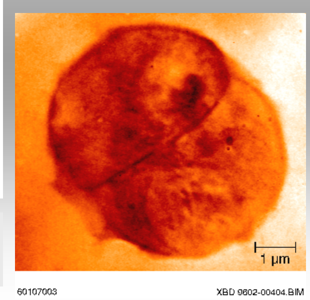
Fullfield Microscope

Conventional x-ray microscope XM-1 at the ALS





Instrumentation operated by Center for X-ray Optics at ALS, Berkeley, CA (USA)

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X-ray microscope schemes

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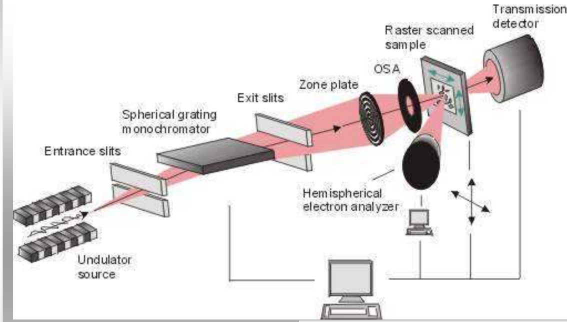
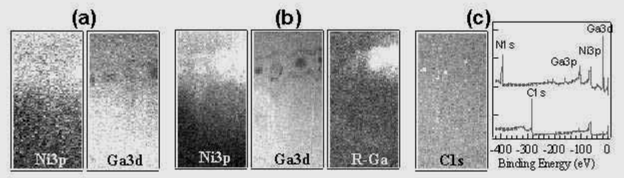


Scanning Microscope

Ni 3p and Ga 3d images (25x50 µm2) taken at (a) 25º C and (b) after annealing to 300º C, the R-Ga image in (b) manifests lateral variations in the interfacial reaction (c) C 1s image and entire spectrum measured in the C-rich spots (bottom) and in the non-defect region (top)

ESCA-microscopy beamline operated at ELETTRA



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Spatial resolution

ultimate limit
experimental limit

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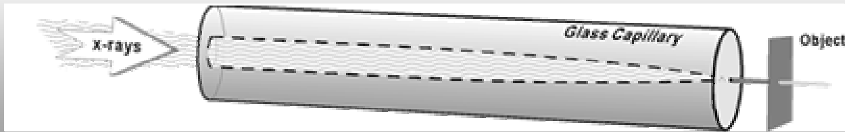
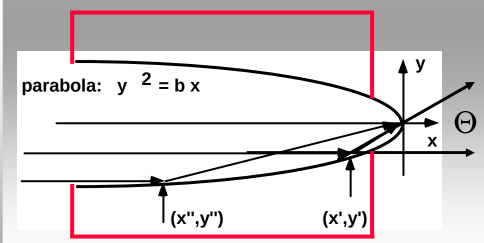
Reflection

SINGLE BOUNCE elliptical/parabolic capillary





Achromatic objective

$\Theta = 2\Phi_{crit} = 2\mathrm{sqrt}(2\delta) = NA$

$R_{ult} = \lambda/(4\ \mathrm{sqrt}(2\delta))$

recall: $\delta \approx a\,\lambda^2$

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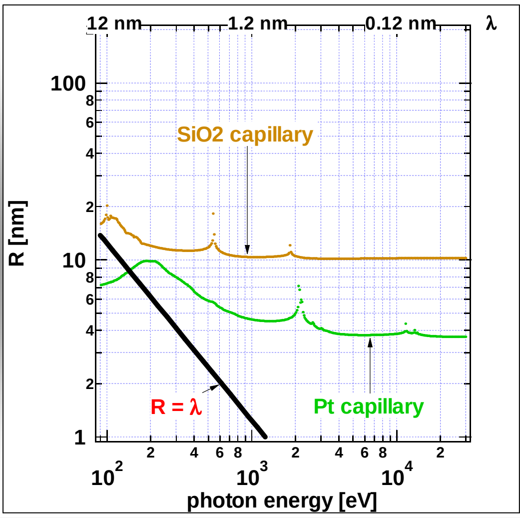

Yes: R = f(Z)
R ≈ 4 nm for Pt (Z=78)

R_{exp} ≈ 10.000 nm (2D)

figure error limited (Bilderback, CHESS)

no successive figure correction possible

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Spatial resolution

ultimate limit
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Reflection

Beam compression in multibounce capillary

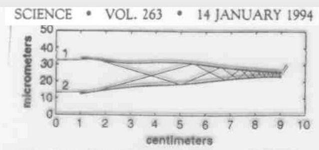
SCIENCE • VOL. 263 • 14 JANUARY 1994

Fig. 1. Profile of the inner diameter (ID) of a capillary measured with an optical microscope. The entering ID is 22 µm and the exit ID is 3 µm. The calculated trajectories of two rays from a parallel x-ray beam are shown. Ray 1 undergoes 12 successive bounces with a net throughput of 57%, as calculated by a two-dimensional ray-tracing program that includes the x-ray reflectance for each bounce. Ray 2 undergoes 11 reflections with a net throughput of 61%. The average reflectivity per bounce exceeds 95%, and the total deflection angles are 2.3 and 2.2 mrad, respectively.

Donald H. Bilderback, 201

Yes: R ≈ 10 nm for glass
R ≈ 4 nm for Pt

R_{exp} ≈ 50 nm (2D), but inefficient

good efficiency for R_{exp} ≈ 5.000 nm (2D) (commercially available)

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Spatial resolution

ultimate limit
experimental limit

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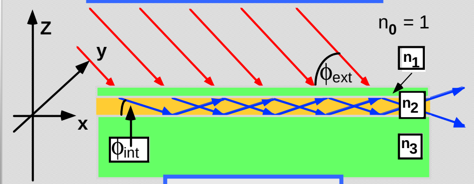
Channeled radiation

X-ray waveguides



chromatic

Snell's law:
$\phi_{ext} = \mathrm{sqrt}(\phi_{int}^2 + \phi_{crit}^2)$

for $\delta_2 << \delta_3$:
$D_{min} = \lambda/(2\ \mathrm{sqrt}(2\delta_3))$
$R_{ult} = \lambda/(4\ \mathrm{sqrt}(2\delta))$
seen before

Fwhm beam size at exit is D/2.
Beam to be reflected internally
$\phi_{int} > \Phi_{crit}$
creates standing wave
$D = \lambda / 2 \sin \phi_{int}$

Bergemann et al, PRL 2003):
There is a natural limit for channeled radiation!
e.g. waveguides, tapered capillaries, long slits

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Spatial resolution

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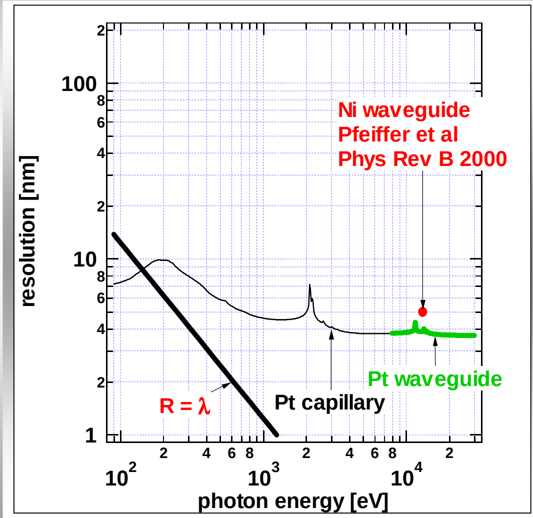

D_{exp}=10 nm (1D),
but inefficient

D_{exp}=70 nm (R=35 nm)
is very efficient (1D)
(Jark et al, APL 2001)

2-dim. version is tested
R = 35 nm x 65 nm
(Pfeiffer et al,
Science 2002)

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Spatial resolution

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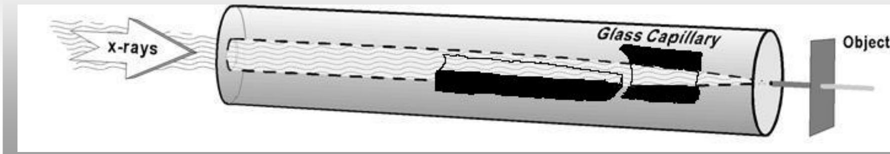
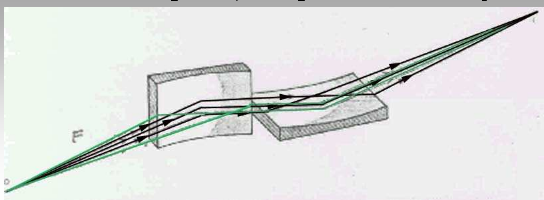
Back to mirrors

Reflection

Cut capillary in pieces, access surfaces



Crossed mirror pair (Kirkpatrick-Baez system)



Spatial resolution

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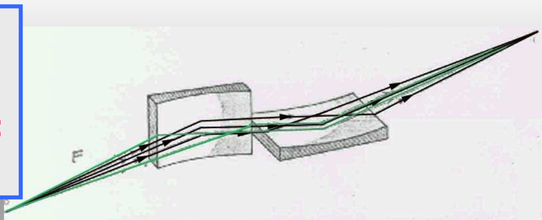
Back to mirrors

Reflection

Crossed mirror pair (Kirkpatrick-Baez system)

Achromatic system
horizontal and vertical focusing are separated: “astigmatic” system



Source → **Focus**

→ or

Synchrotron radiation sources

or

Spatial resolution

ultimate limit
experimental limit

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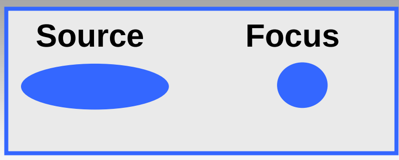
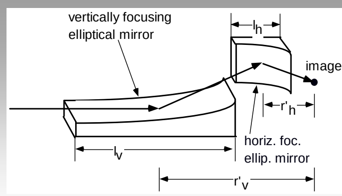
Rule of thumb for crossed mirror pair (Kirkpatrick-Baez system):

Mirror length ≈ focal length (details in appendix)

then

NA ≈ 0.4 Φ_{crit} and in practise R_{ult} = 5 $R_{ult,cap}$





Spatial resolution

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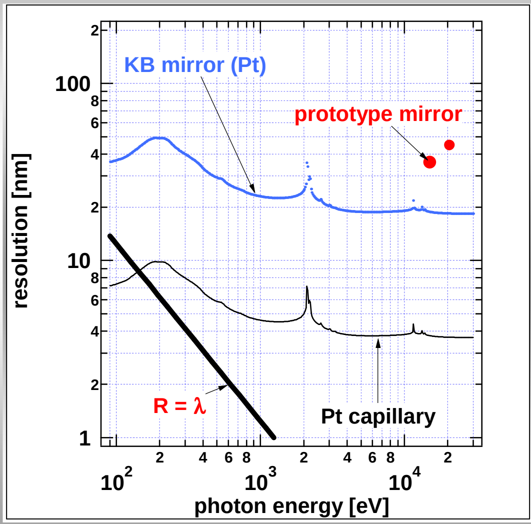

In practise

R_{ult} ≈ 20 nm for Pt

R_{exp} = 36 x 48 nm @15 keV
(H. Yumoto, RSI 2005)

figure error limited

Can we increase the angles of incidence?

Yes, in Multilayer mirrors

Multilayer coatings

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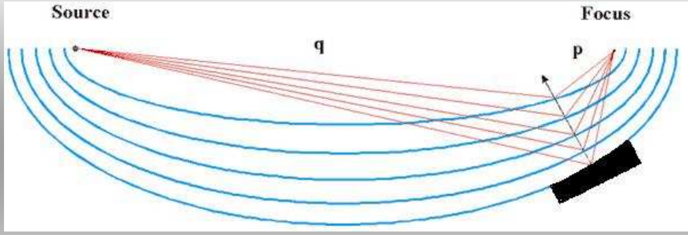
Reflect the beam at many partly transparent interfaces!
Then we have an artificial crystal with free choice for d.



Commonly known also as Goebel mirrors

see e.g. www.bruker-axs.de/products/gd/goebel_mirrors.php

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Field propagation into thin films

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Can be calculated

Solution of Parratt (Phys. Rev. 95, 359 (1954))

$E_{\text{tang}} = \text{const}$ at interface

$a_j =$ amplitude factor $\quad a_j = exp\left(-i\pi \frac{g_j d_j}{\lambda}\right)$

$d_j =$ thickness, $\lambda =$ wavelength,

$g_j = \tilde{n}_j \sin\theta_j \qquad \tilde{\varepsilon}_j = \tilde{n}_j^2 \qquad \tilde{n}_j = 1 - \delta + i\beta$

$$a_j E_j + a_j^{-1} E_j^R = a_{j+1}^{-1} E_{j+1} + a_{j+1} E_{j+1}^R$$

$$g_j \left(a_j E_j - a_j^{-1} E_j^R\right) = g_{j+1} \left(a_{j+1} E_{j+1} - a_{j+1} E_{j+1}^R\right)$$

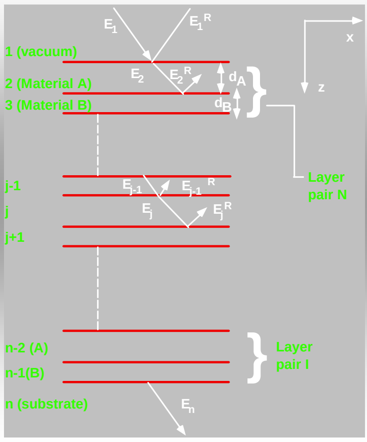
Solution => Recursion equation

$$R_{j,j+1} = a_j^4 \left[\frac{R_{j+1,j+2} + J_{j,j+1}}{R_{j+1,j+2} \; J_{j,j+1} + 1}\right] \qquad \mathbf{R} = \frac{I}{I_0} = |R_{12}|^2$$

$$R_{j,j+1} = a_j^2 \frac{E_j^R}{E_j}$$

$$J_{j,j+1}(s-pol) = \frac{E_j^R}{E_j} = \frac{g_j - g_{j+1}}{g_j + g_{j+1}}$$

$$J_{j,j+1}(p-pol) = \frac{g_j/\tilde{n}_j^2 - g_{j+1}/\tilde{n}_{j+1}^2}{g_j/\tilde{n}_j^2 + g_{j+1}/\tilde{n}_{j+1}^2}$$



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Field propagation into thin films

Do not be afraid of the programming.

The job is already done by the Center for X-ray Optics at LBNL at Berkeley, CA (USA): look under

http://www-cxro.lbl.gov/optical-constant
http://www-cxro.lbl.gov/optical-constant/multi2.html

If you want to analyse data, ask the ESRF for the XOP software package, which contains the program IMD of David Windt.

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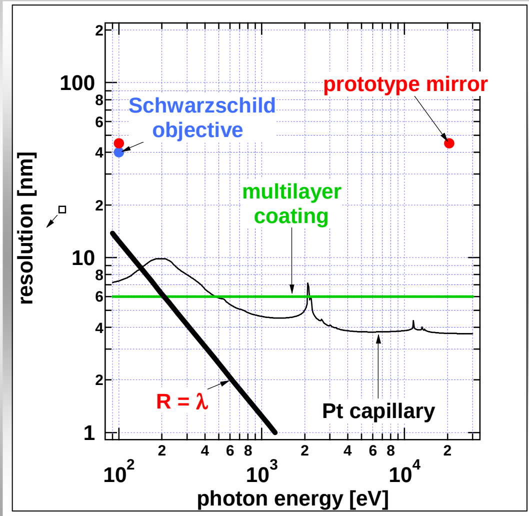
Spatial resolution

ultimate limit
experimental limit



Add multilayer coating (now is CHROMATIC)
still NA ≈ 0.4 Φ
but λ=2d sin(Φ):
R = 2.5 d
d ≥ 3 nm is efficient

R_{exp} ≈ 45 µm (1D)
(Hignette, ESRF, 2005)

figure error limited

Spatial resolution

ultimate limit
experimental limit

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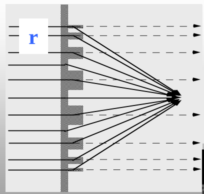
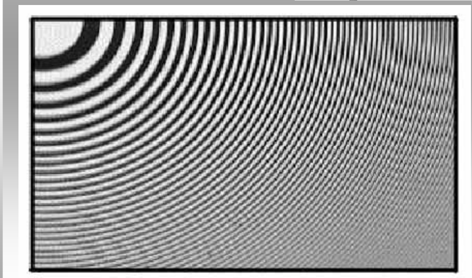
Diffraction

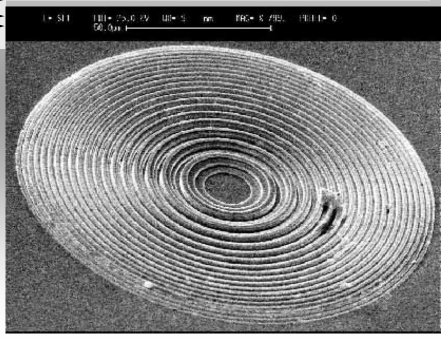
Highly CHROMATIC



Fresnel zone plates
see Kirz, Schmahl

Zone-plates produced at INFM-TASC laboratory at ELETTRA





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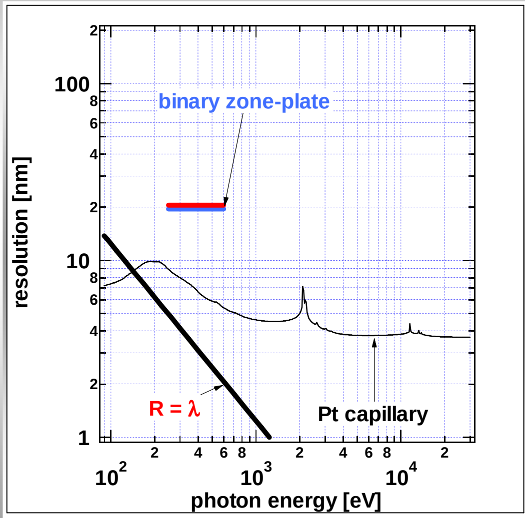

For binary zoneplates (opaque in soft x-rays)

r outermost period

R = r/2

R_{exp} ≈ 20 nm@2 nm (2D) (CXRO, Berkeley,2005)

line width limit ≈ 20 nm lithographic processes

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Spatial resolution

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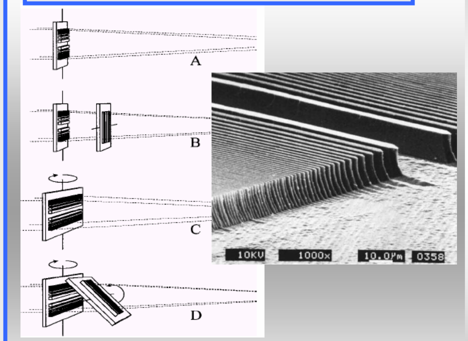
Rings (thickness t) become transparent for x-rays.
Need phase zoneplates:

rings retard by π
$t= \lambda/(2\delta)$ and for circular ZP
$r_{min}=t/8$ $R_{prac}= r/2 = \lambda/(32\delta)$
$R_{exp} \approx 90$ nm for r=206 nm
$t \approx 4.4$ r @ $\lambda=0.154$ nm
(Yun et al, RSI 1999) (2D)

C. David et al, APL 2001



$r_{min} \approx t/50$ but $r_{min} > 40$ nm
$R_{prac}= \lambda/(200\delta) > 20$ nm

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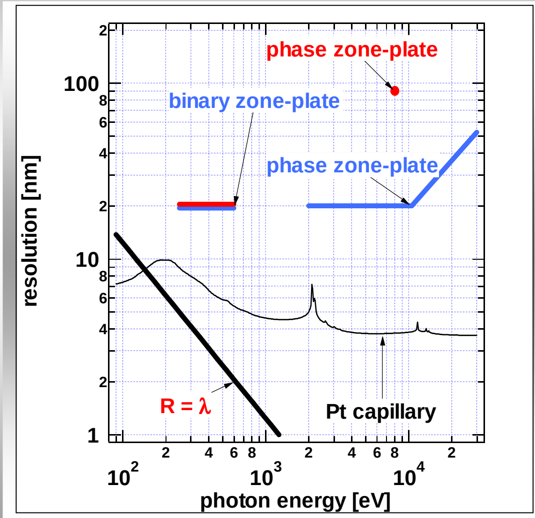
In memory of J.C. Fuggle and L. Fonda, Trieste, 11/05/2006

Spatial resolution

ultimate limit
experimental limit

μXFA beamline and multilayer laboratory



Phase zoneplates have better efficiency than binary zone-plates

out-of-phase zoneplates could produce smaller focii above 10 keV with reduced efficiency

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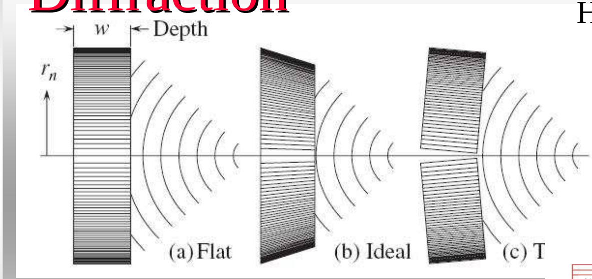
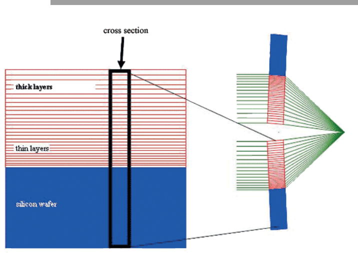
Diffraction

Multilayer Laue lens
H.C. Kang et al, PRL 2006



Ideally beam is reflected at interfaces to focus

Multilayer deposition starting with thinnest layer (d=10 nm) for a total of 12.4 µm



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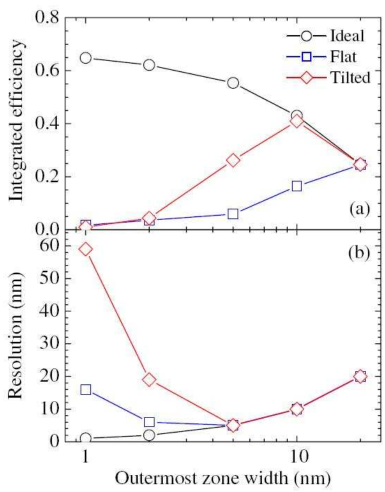
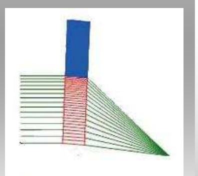


For 19.5 keV photon energy

Flat: phase zoneplate
Ideal: tapered interfaces
Tilted: parallel interfaces

$R_{ult,tilted}$ = 5 nm
$R_{ult,ideal}$ = 1 nm

R_{exp} = 30 nm (1D)



Experiment at half lens
H.C. Kang et al, PRL 2006

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