Spatial resolution

ultimate limit
experimental limit

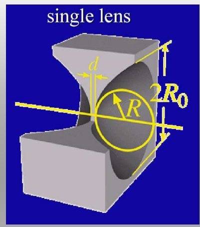
µXFA beamline and multilayer laboratory

Refraction

www.accel.de

Chromatic lenses

Compound refractive lenses (concave)
Snigirev et al, NATURE 1996
patents: Tomie 1995



Prod.: Lengeler @RWTH Aachen, D

x-rays: $n = 1 - \delta - i\beta < 1$

need of concave and parabolic lenses

$f = R_0/(2\delta)$ $l = 1/(\rho*[\mu/\rho])$

lens transmission:

$T(y) = \exp(-y^2/2f\delta l)$

for d=0 Gaussian with

$\sigma = \mathrm{sqrt}(f\delta l)$

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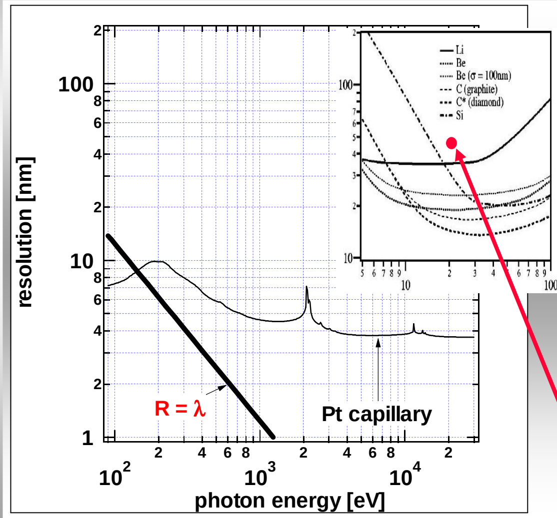

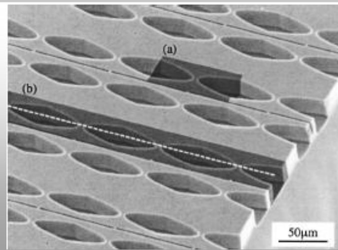

No: R_0 and N are free

$R = 0.25\lambda \mathrm{sqrt}[R_0/(Nl\delta^2)]$

R_{exp}=47 x 55 nm @ 21 keV
for mini-lens in Si
(Schroer et al, APL 2005)

Spatial resolution

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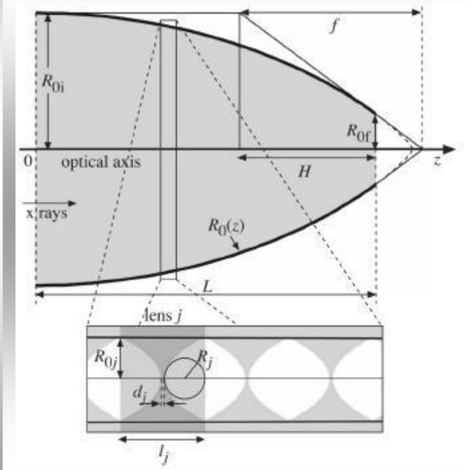
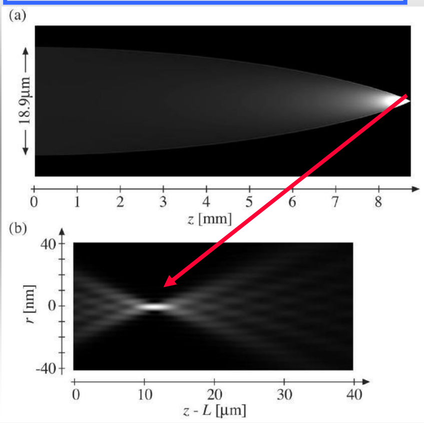
Schroer et al (PRL 2005):
Better focus adiabatically
to R=4.74 nm @ 27.6 keV
R_{exp} not yet (production 2D?)





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

Spatial resolution

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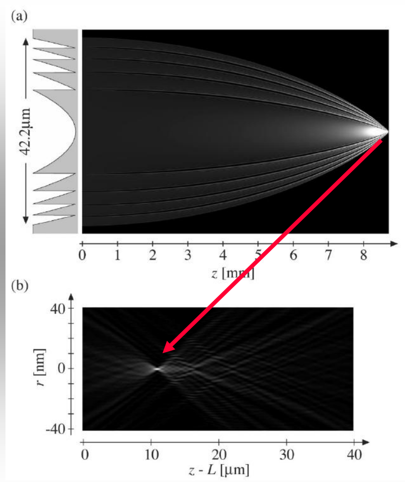
µXFA beamline and multilayer laboratory



Schroer et al (PRL 2005):
Better "lighten" the lens with "Fresnel's lighthouse lens strategy" and focus adiabatically to
R=2.21 nm @ 27.6 keV
R_{exp} not yet (production 2D?)

What to do?
"Lighten" a refractive lens by removing all material, which retards the field by multiples of 2π

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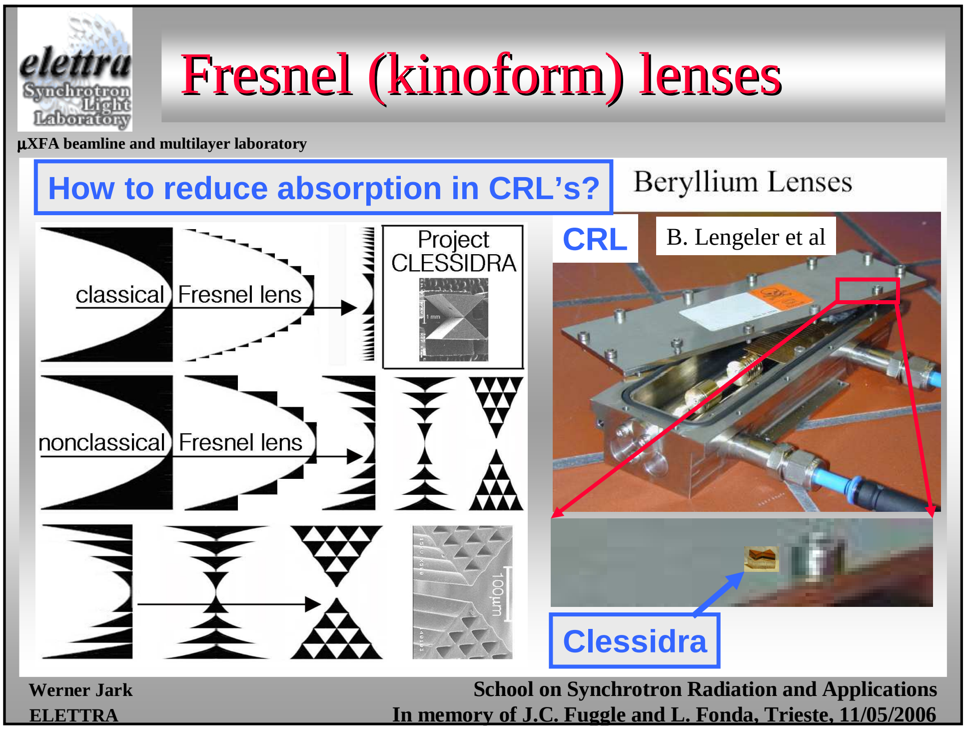
Fresnel (kinoform) lenses
elettra Synchrotron Light Laboratory
µXFA beamline and multilayer laboratory
How to reduce absorption in CRL's?
Beryllium Lenses
classical
Fresnel lens
Project CLESSIDRA
nonclassical
Fresnel lens
100µm
CRL
B. Lengeler et al
Clessidra
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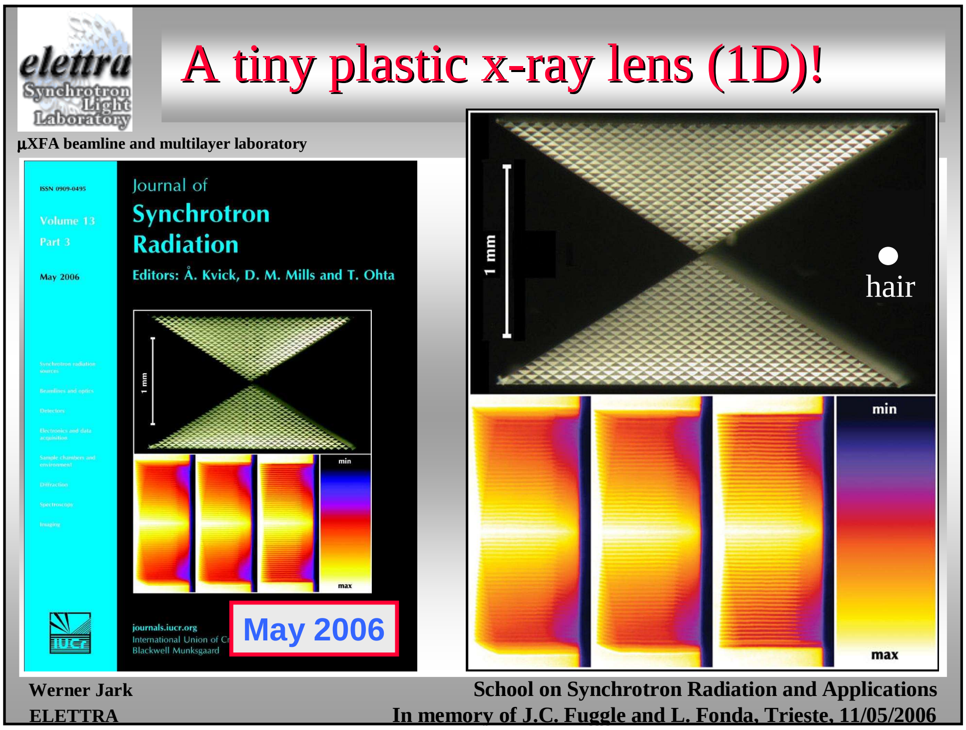
A tiny plastic x-ray lens (1D)!
elettra Synchrotron Light Laboratory
µXFA beamline and multilayer laboratory
ISSN 0909-0495
Volume 13
Part 3
May 2006
Journal of
Synchrotron
Radiation
Editors: Å. Kvick, D. M. Mills and T. Ohta
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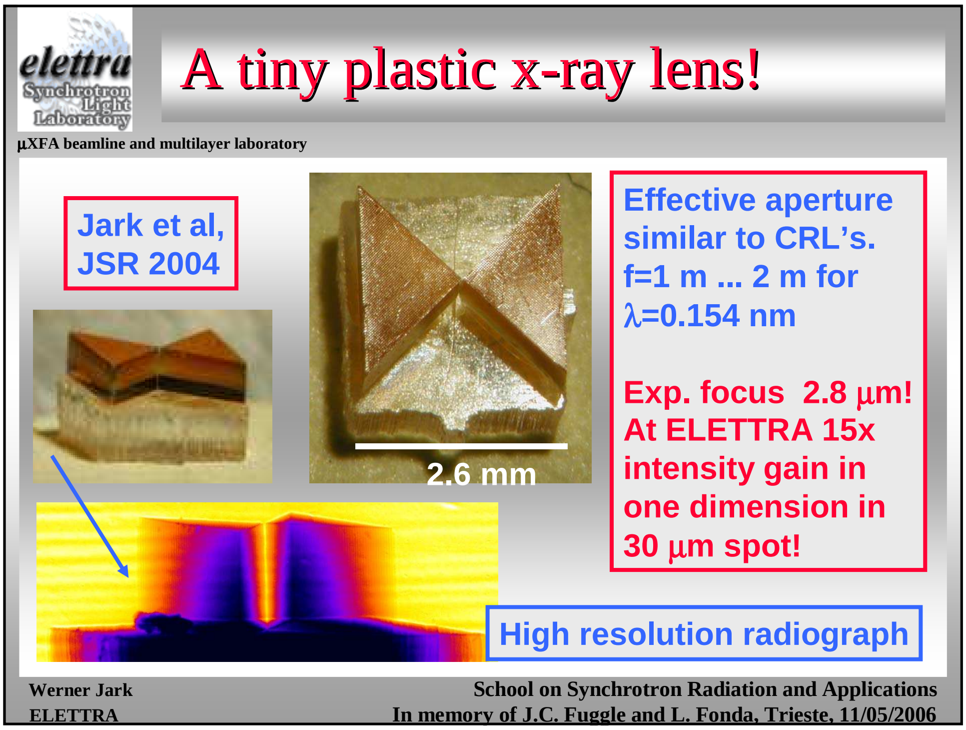

A tiny plastic x-ray lens!
µXFA beamline and multilayer laboratory
Jark et al, JSR 2004
2.6 mm
Effective aperture similar to CRL's. f=1 m ... 2 m for λ=0.154 nm
Exp. focus 2.8 µm! At ELETTRA 15x intensity gain in one dimension in 30 µm spot!
High resolution radiograph
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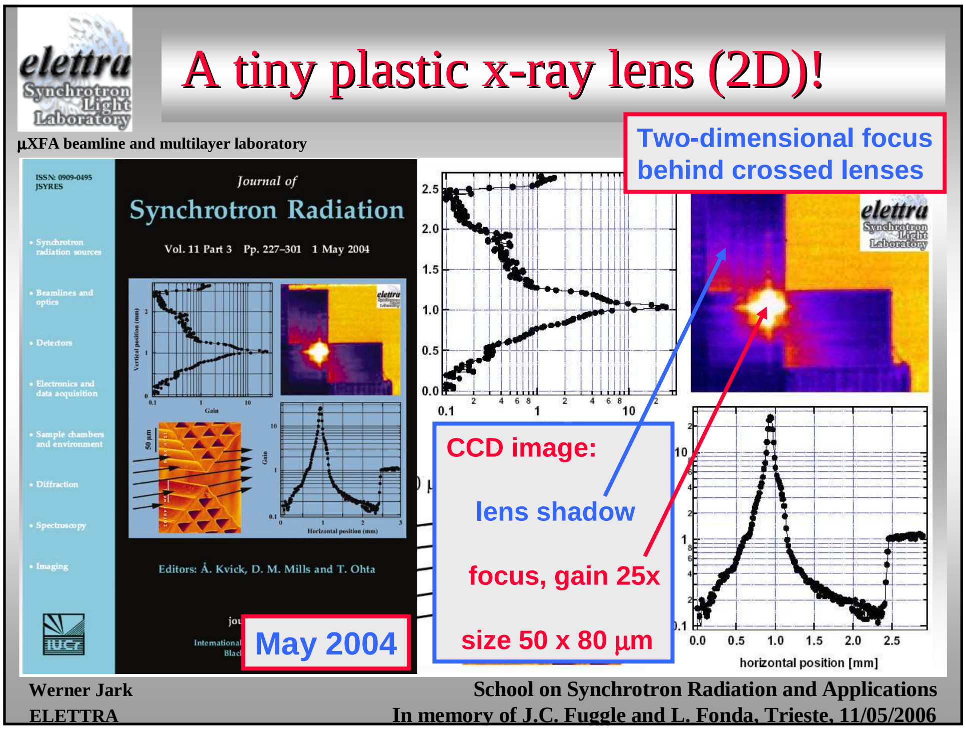

A tiny plastic x-ray lens (2D)!
µXFA beamline and multilayer laboratory
Journal of Synchrotron Radiation
Vol. 11 Part 3 Pp. 227–301 1 May 2004
Editors: Å. Kvick, D. M. Mills and T. Ohta
May 2004
Two-dimensional focus behind crossed lenses
CCD image:
lens shadow
focus, gain 25x
size 50 x 80 µm
horizontal position [mm]
Werner Jark
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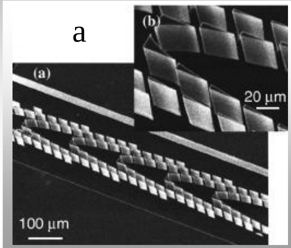
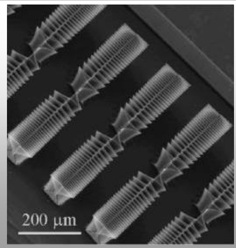
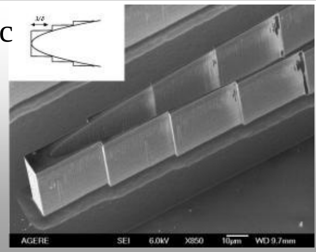
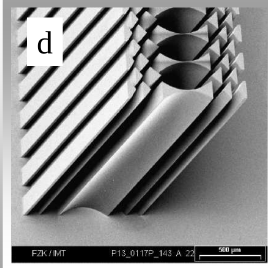
other Fresnel (kinoform) lenses

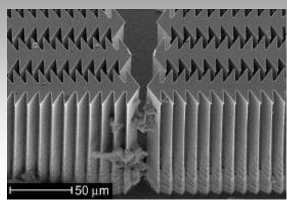
µXFA beamline and multilayer laboratory

a


b


c


d


e


No limit for R! Decreases with feature size!

R_{exp} ≈ 0.6 µm (1D with c)

a) Aristov et al, APL2000
b) Snigireva et al, NIM2001
c) Evans-Lutterodt, OE2003
d) ANKA, Karlsruhe, 2005
e) Cederstroem, JSR 2005

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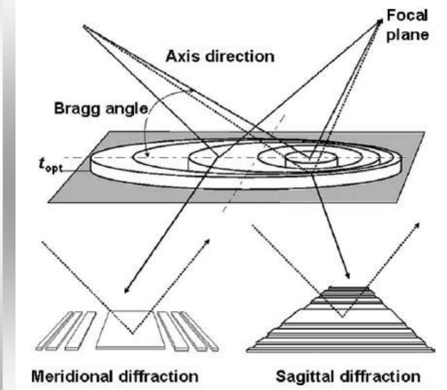
Spatial resolution

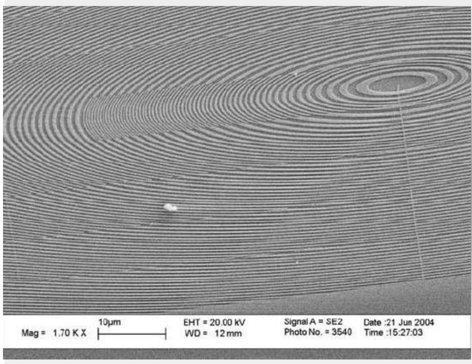
ultimate limit
experimental limit

µXFA beamline and multilayer laboratory

Diffraction



Bragg-Fresnel reflection zone-plate
Michette et al, Opt. Commun, 2005



Combine diffraction of different order

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Spatial resolution

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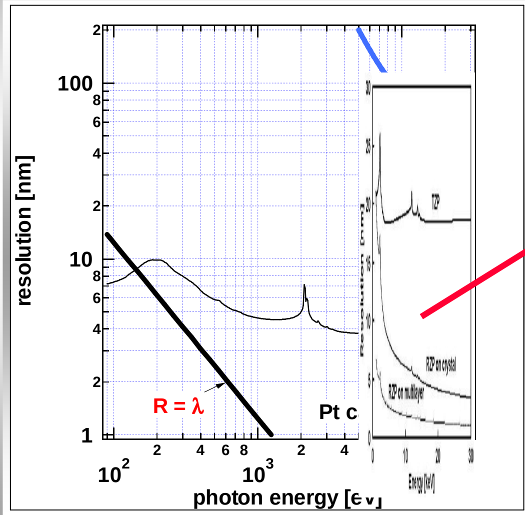
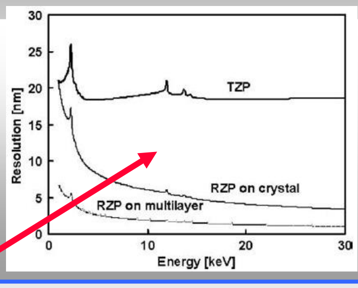
µXFA beamline and multilayer laboratory





Once more multilayer coating

$R_{ult} \approx 2 \times 4$ nm @ 30 keV

R_{exp} not yet

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Some problems: Spatial coherence

µXFA beamline and multilayer laboratory

Diffraction limited spot size is obtained with spatially coherent incident radiation

A = lens aperture Q = source distance

$S\,(A/Q) = \lambda$

$\Longrightarrow$

$Q = SA/\lambda$

e.g. S=30 µm, A=1 mm, λ =0.154 nm: Q=200 m!!
S= 30 µm, A=0.02 mm, λ=0.154 nm: Q=4 m!!

Is your aperture spatially coherently illuminated?
Is your demagnification of order of 10,000?

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Some problems: Depth of focus

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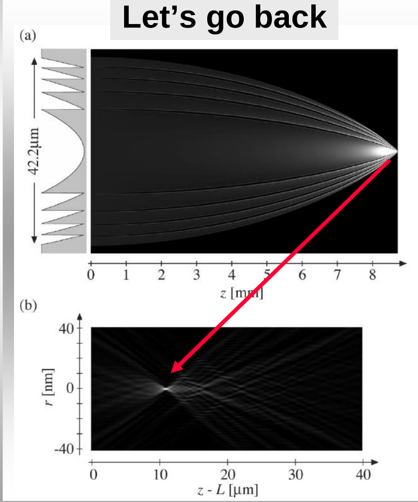
Let's go back



Schroer et al, PRL 2005
Δf<1 µm @ 27.6 keV!

assume 2NA=10 mrad=0.01
then Δf≈4 µm for s≈40 nm
Δf≈100 µm for s≈1000 nm

Attenuation length l in Au/Si
l = 16/2600 µm @ 27.6 keV
l = 4.5/140 µm @ 10 keV
l = 0.04/0.43 µm @ 0.5 keV

Scanning or imaging?

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Some problems: spot size?

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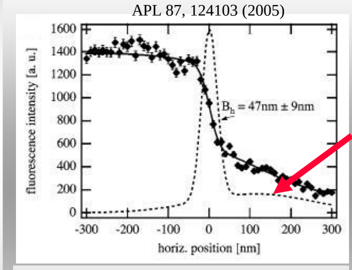
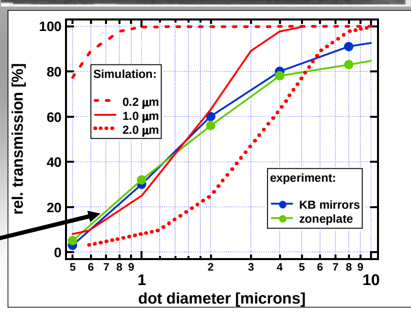
Classical knife-edge test

CRL: C.G. Schroer et al,
APL 87, 124103 (2005)



Fit to integrated data

Fluorescence from test pattern
A.C. Thomson et al, Proc. SPIE
4145, 16 (2000)



R from knife-edge (fwhm)
KB mirror: 1.0 µm
zone-plate: 0.2 µm

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Summary: Spatial resolution

μXFA beamline and multilayer laboratory

- Simpler optics may bring us ideally to R≈4-6 nm (capillaries, waveguides, tilted Laue lenses, adiabatic CRL's)
- More sophisticated objects are capable of R≈1-2 nm (ideal Laue lenses, adiabatic kinoform refractive lenses, Bragg-Fresnel reflection zone-plates)
- Is R≈λ possible?
- An X-ray waveguide could provide already R≈5-6 nm (but only 1D, no further recent efforts)
- Fresnel zone-plates have R≈20 nm (better in imaging)
- Many other systems could arrive at about R≈30-45 nm

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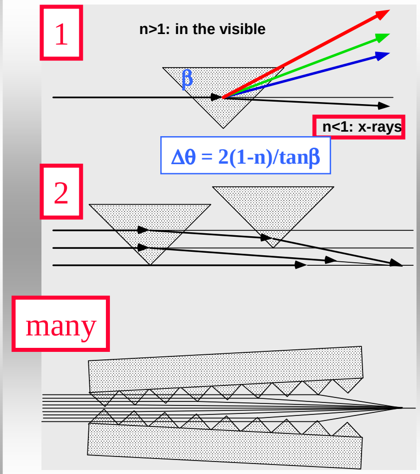
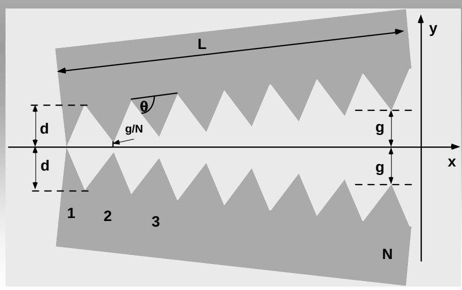
X-ray Zoom lens: Do-It-Yourself!

μXFA beamline and multilayer laboratory



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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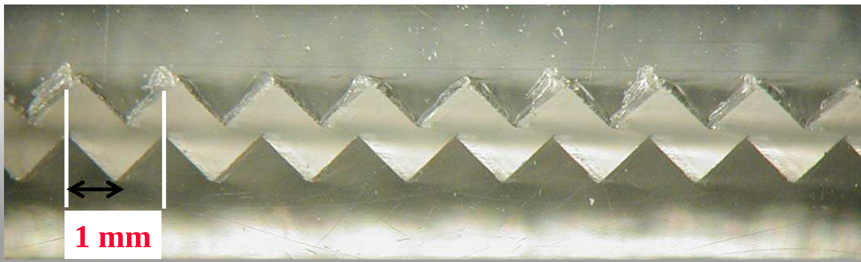
Get it almost for free

µXFA beamline and multilayer laboratory



Sawtooth comb milled into PLEXIGLASS in ELETTRA workshop [Marco De Gregorio, Gilio Sandrin]

For geometrical optics it is a lens with parabolic transmission function, i.e. an approximation of CRL

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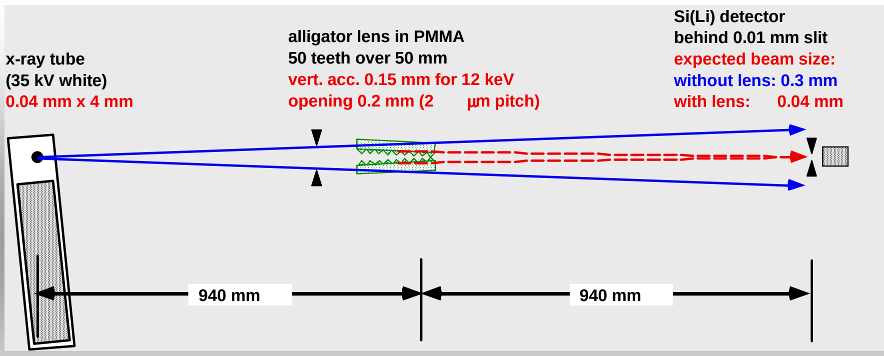
Test it at home

µXFA beamline and multilayer laboratory



With an average transmission of 0.85 in the effective aperture an intensity gain of <u>g = 0.85 * 0.3/0.04 = **6.3**</u> is expected

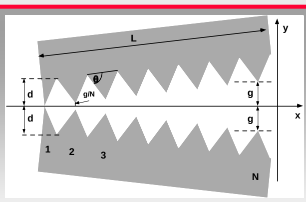
Results (1D)

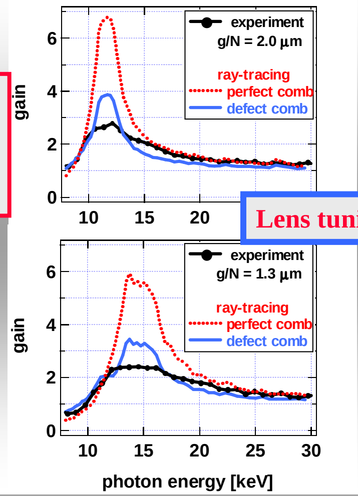
µXFA beamline and multilayer laboratory

You get gain!

Jark, X-ray spectrom. 2004

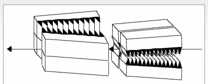
Open/close the alligator mouth (lens):
a) tunable large bandpass x-ray monochromator!
b) tunable beam collimator





Lens tuning

2D with crossed pair



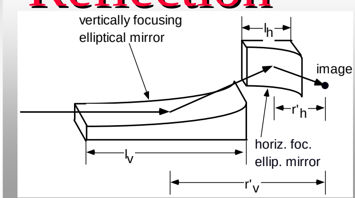
Appendix: Spatial resolution in more detail

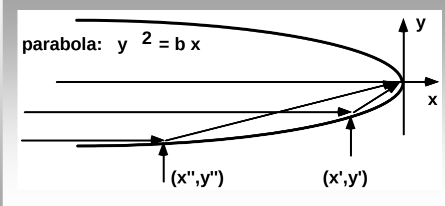
ultimate limit
experimental limit

µXFA beamline and multilayer laboratory

Reflection

Crossed mirror pair (Kirkpatrick-Baez system)





- Ideally elliptical mirrors needed
- approximate as parabola
  $y=(bx)^{1/2}$, $\Delta y/\Delta x = 0.5\,(b/x)^{1/2}$
- for x=x': $\Delta y/\Delta x\,(x') = \Phi_{crit}$
- then $b=(2\Phi_{crit})^2\,x'$ and at x=x'':
  $\Delta y/\Delta x\,(x'') = \Phi_{crit}\,(x'/x'')^{1/2}$
- deflection angle is $2\,\Delta y/\Delta x$
- and convergence angle in focus $\Delta_{(h,v),f} = 2$ NA
  $= 2\,\Phi_{crit}[1-(x'/x'')^{1/2}]$
- Mirror size parameter:
  $q=l/r=|x''-x'|/r$

ultimate limit
experimental limit

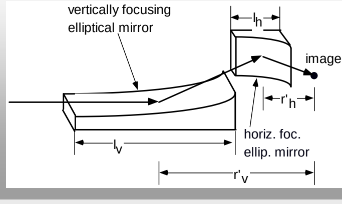
Spatial resolution

µXFA beamline and multilayer laboratory

In more detail

Reflection

Crossed mirror pair (Kirkpatrick-Baez system)



- $$NA = \Phi_{crit}\left(1 - \frac{\sqrt{2-q}}{\sqrt{2+q}}\right)$$
- **2 mirrors just touch with**
  $q_h = l_h/r'_h = l_v/r'_v = q_v = q$
  $r'_h + 0.5\, q\, r'_h = r'_v - 0.5\, q\, r'_v$
  we put $r'_v = m\, r'_h$:
  then $q = 2\,(m-1)/(m+1)$
- **<u>at ELETTRA m=5:</u> <u>q = 1.33</u>**
  $\Delta_{h,f} = \Delta_{v,f} = 1.1\ \Phi_{crit} = 2\ NA$
- **more realistic $2\ NA = \Phi_{crit}$**

<u>OPERATIONAL</u> example:
ESRF (bendable flat mirror):
f=95 mm and l=90 mm
$2\ NA = 0.8\ \Phi_{crit}$
$R = \lambda/(0.8\ \mathrm{sqrt}(2\delta)) = R_{prac}$
$= 5 * R_{single\ bounce\ capillary}$
exp: Φ =2.2 mrad at 20.5 keV

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