X-Ray Microfocusing Optics

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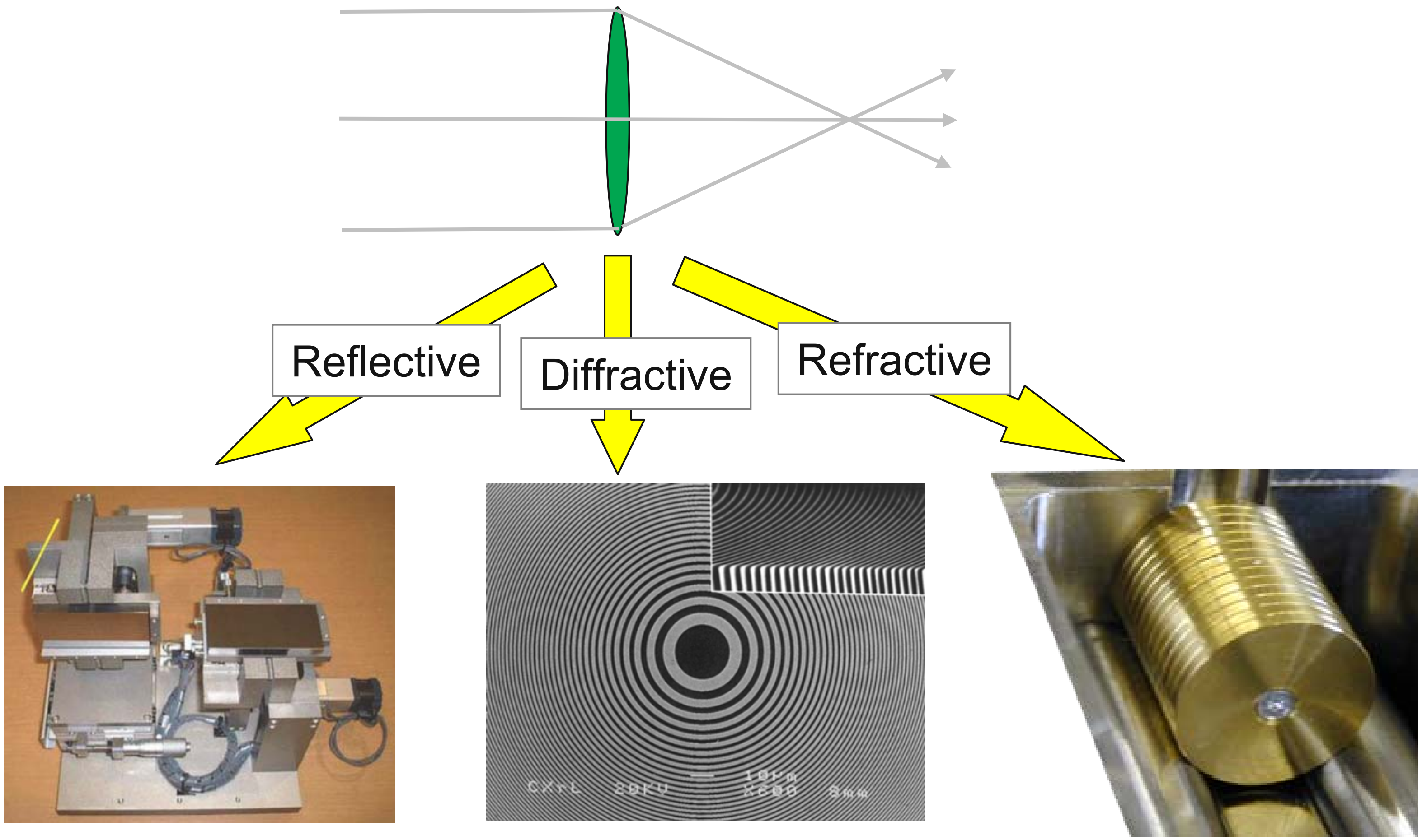
Advanced Photon Source

Outline

- Introduction
- General considerations
- Reflective optics
  Diffractive optics
  Refractive optics
- Future prospects

Introduction

- Optics that focus x-rays to a spot size ≤ 10 micron

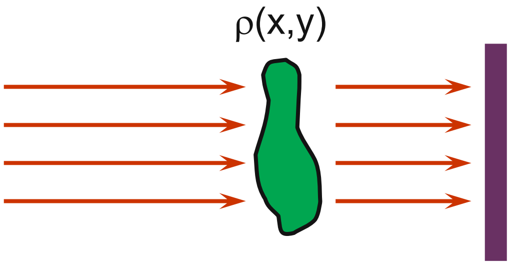


When to use microfocusing optics:

- For x-ray microscopy
  - Most samples are heterogeneous, from micron down to nm scale
- Increased flux density
  - Gain ~ 10^6 is possible, hence higher sensitivity (signal/background)
- Enable smaller samples or new sample environment

X-ray Microscopy

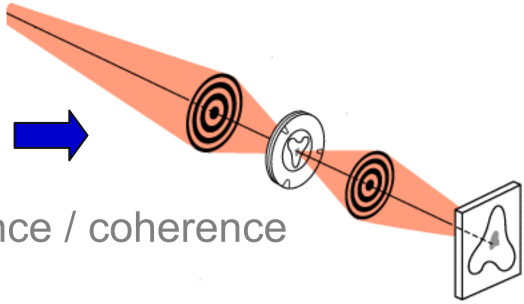
Lecture by I. McNulty on Oct. 3



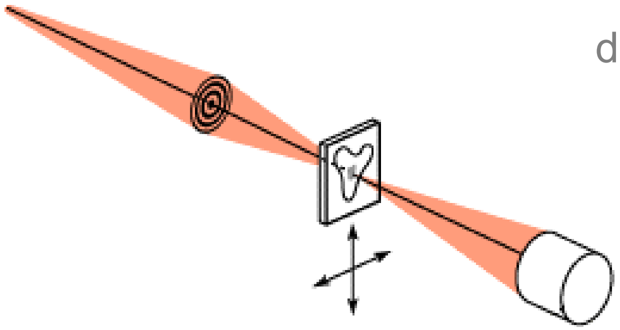
Direct imaging (radiography)*

with magnification in visible light

Transmission microscope (TXM)



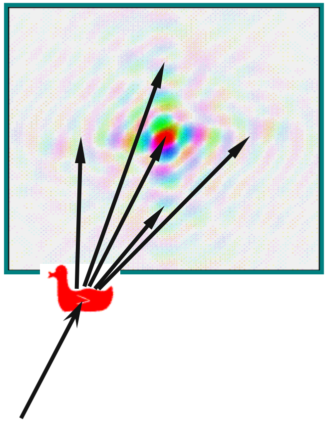
depends only on total flux, but not brilliance / coherence

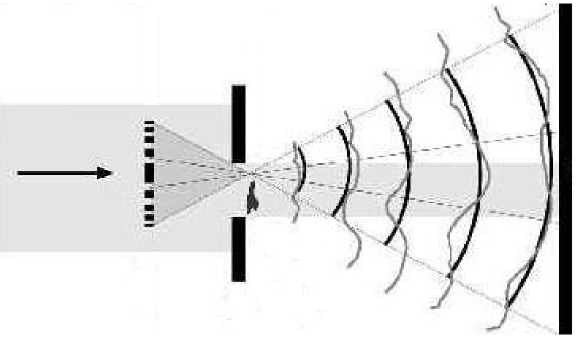


Scanning microscope (SXM)

depends only on coherent flux, directly benefits from reduced emittance

Coherent diffraction imaging*

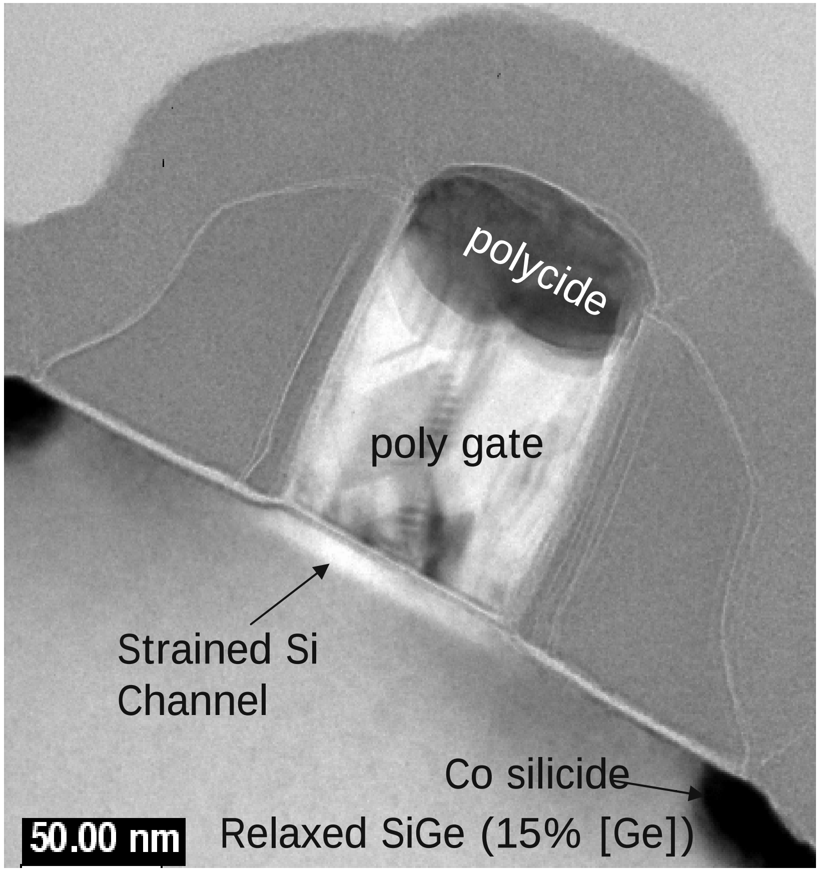


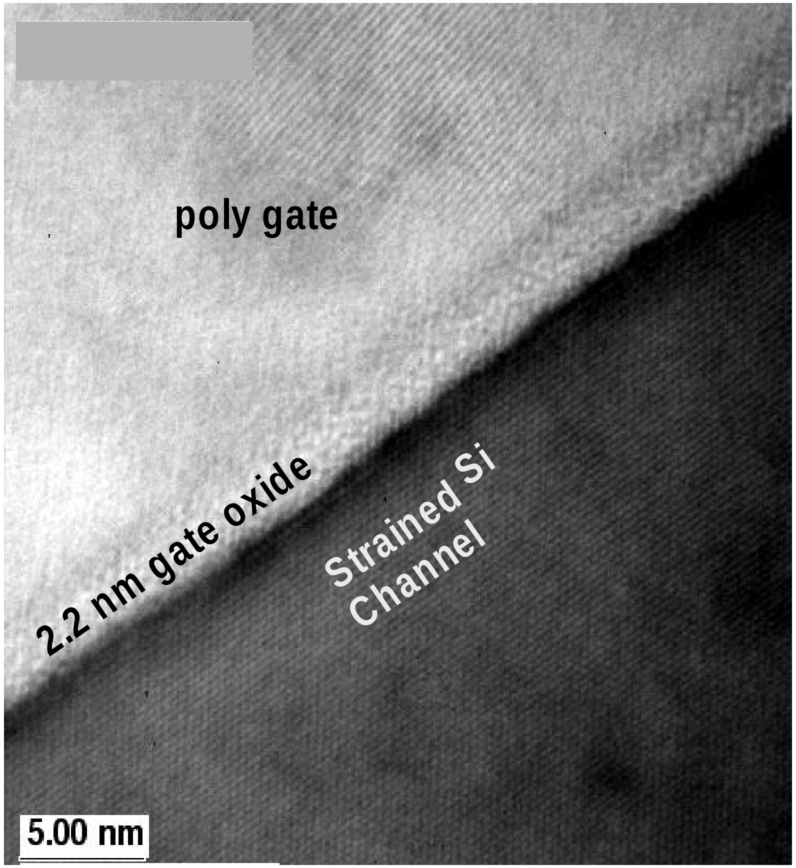


Holography*

** May not require microfocusing*

Cross-sectional TEM of Strained-Si NMOSFET





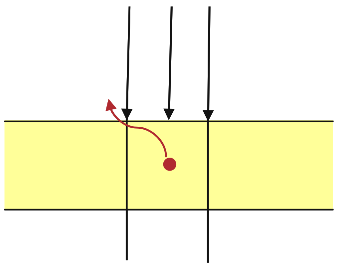
Ken Rim -IBM

- Quality of epitaxial layers maintained during CMOS process steps
- Gate oxide with smooth interface formed by thermal oxidation

=> today's manufacturer's are already able to produce nm scale structures. To probe such small structures meaningfully requires x-ray beam of the same order of magnitude.

Slide courtesy Cev Noyan, with modification

Microfocusing increases flux density



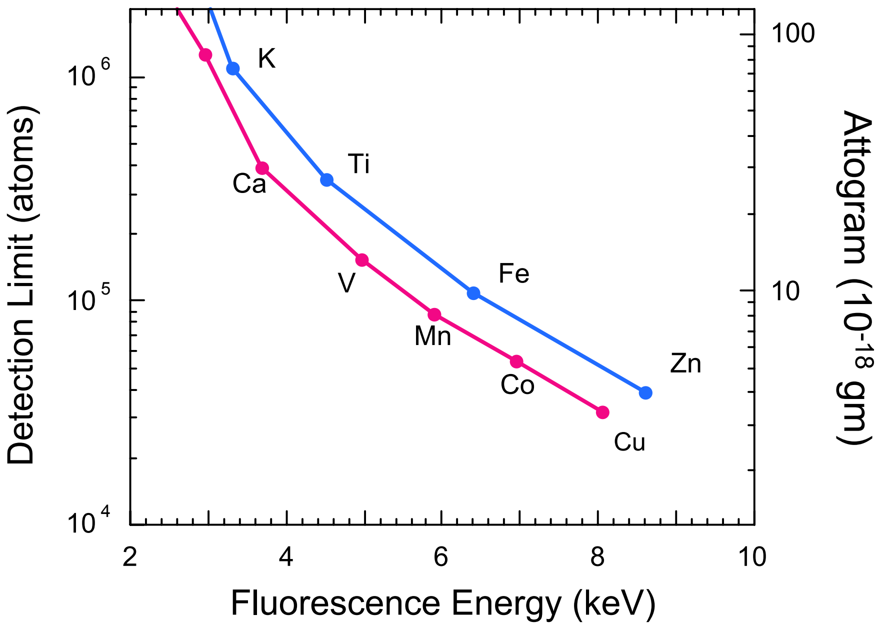
- Focusing increases the signal/background ratio

- For current probes with submicron spot, attogram (10^{-18} gm) of materials can be detected in fluorescence mode

- With a 5-nm probe, sensitivity of zeptogram (10^{-21} gm) or a few atoms is possible

Detection Limit with 1 sec. Dwell Time

0.2 x 0.2 μm^2 spot, E=10 keV

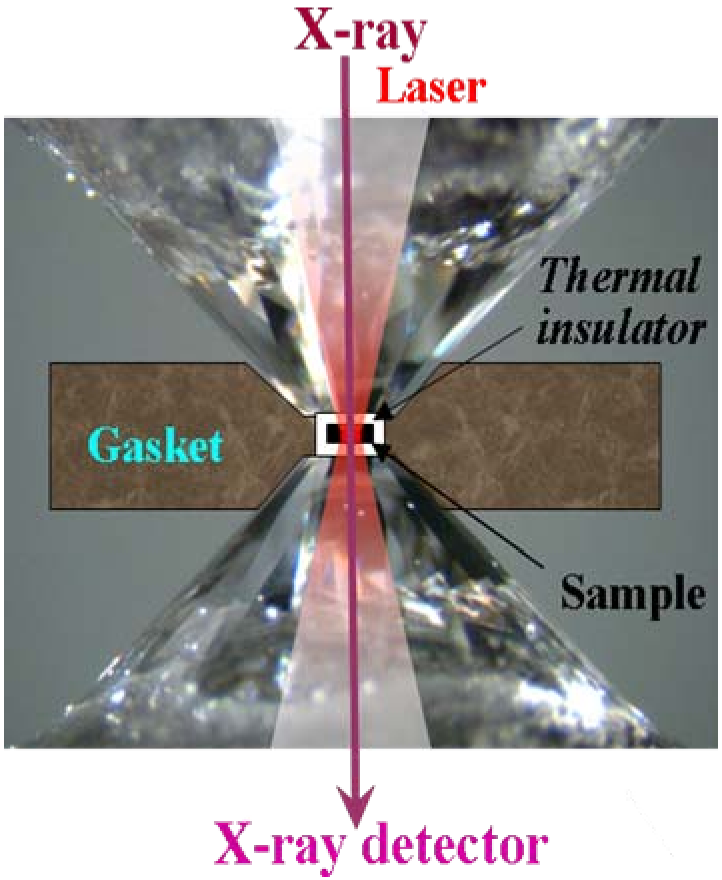


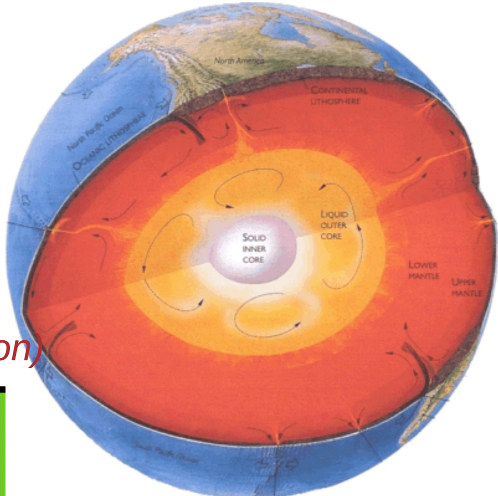
Microbeam for protein crystallography

- Very small crystals: reduce scatter from non-crystalline material
- Selective exposure of small crystal volumes:
  - very asymmetric shape of crystal (e.g. needle): reduce scatter from non-crystalline material
  - very small, well ordered domains
- Reducing radiation damage in exposed volume:
  - photo-electrons travel several μm (~6μm for 18 keV initial energy)
  - large fraction of damaging energy is not deposited in the illuminated volume for micrometer size beams
  - energy deposit per distance traveled is not uniform, very high at end of travel
- Photo-electrons ejected predominantly in direction of electric field vector

New High-Pressure Frontiers with higher spatial resolution

- Diamond Anvil Cell uses focused microbeams at high energy (>30 keV) to probe highest pressure/temperature region
- High pressure: with better focused beams, can use small anvil tips, and greatly extend the accessible pressure from 350GPa $\Rightarrow$ TPa
  - New areas for discovery of materials and phenomena
- High temperature: with smaller probes, can limit the heating area to diffraction limit of laser, thus extend max temperature from 6,000K to 12,400K
- Open up new opportunities for studies of materials under core conditions (P,T)
- Improve ability to understand structures of Giant Planets





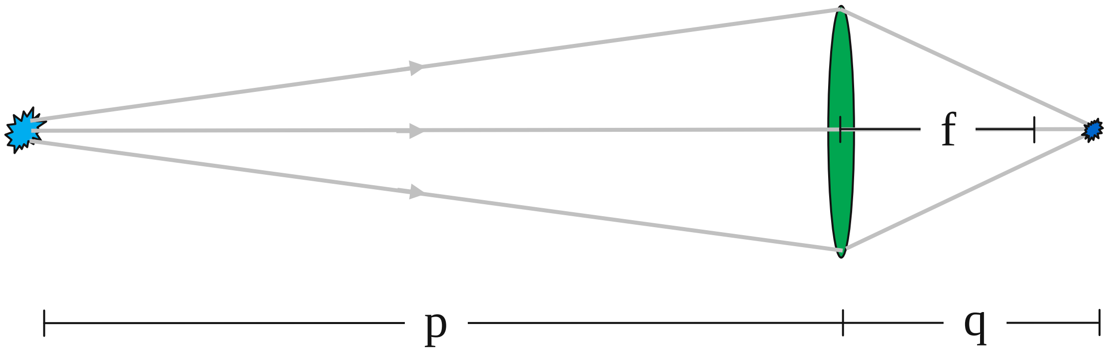
Slide adapted from Steve Sutton (UoC) & David Mao (Carnegie Institute of Washington)

General considerations

- Magnification
- Numerical Aperture
- Resolution
- Depth of Focus
- Chromatic aberration

Geometrical Optics

- Thin-Lens Equation: $\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$



- Magnification: $M = \frac{q}{p}$

- Microfocusing optics produce a demagnified image of the source ($M < 1$).
  Imaging optics produce a magnified image of the sample ($M > 1$).

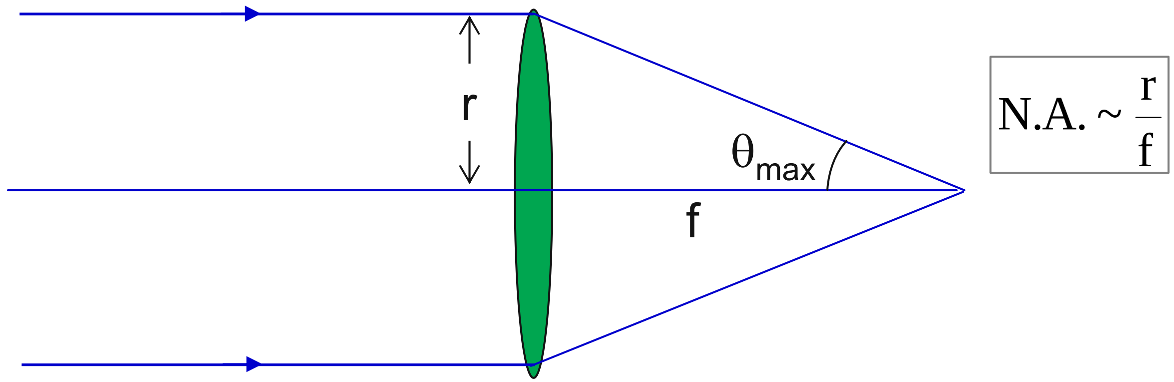
- Some optics can work as both, others only for microfocusing ($M < 1$).

Demagnification

- For synchrotron micro/nano-probes, $M \sim 10^{-2} – 10^{-4}$
- If decreasing focal length becomes difficult, long beamlines (p) will help

Numerical Aperture

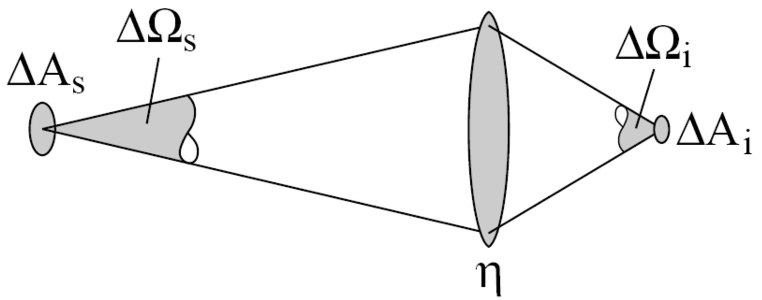
- N.A. = n sin θ_{max} is a measure of the light gathering power $\left(\text{N.A.} = \frac{1}{2(f/\#)}\right)$



- Intimately related to the performance of the optics (focused flux, diffraction-limited resolution, depth of focus, etc.)

Liouville's Theorem

- Phase space density is conserved in a perfect optical system (η = 100%)



Perfect optical system:
$\Delta A_s \cdot \Delta\Omega_s = \Delta A_i \cdot \Delta\Omega_i$

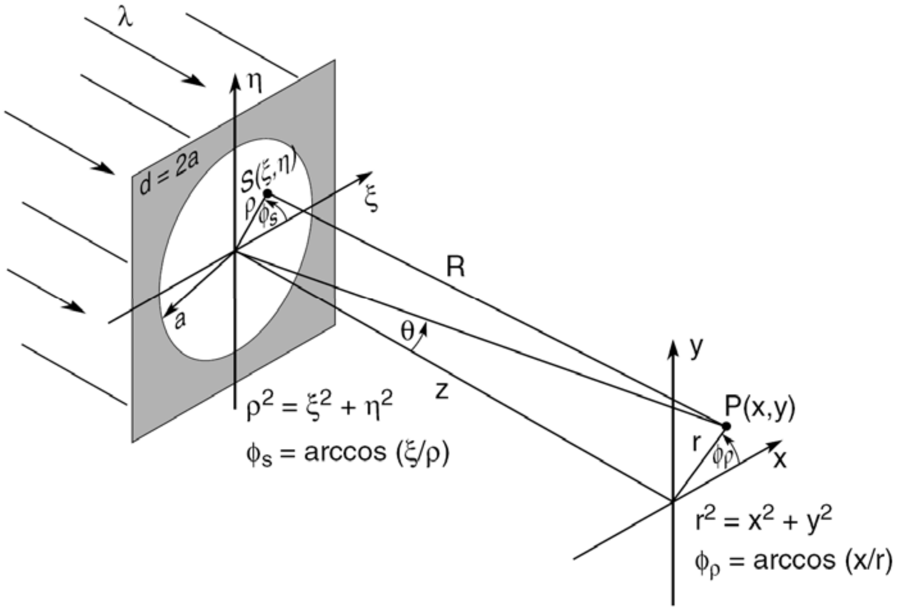
- Microfocusing optics inevitably will increase the angular spread

- Brightness is the radiated power per unit area per solid angle at the source

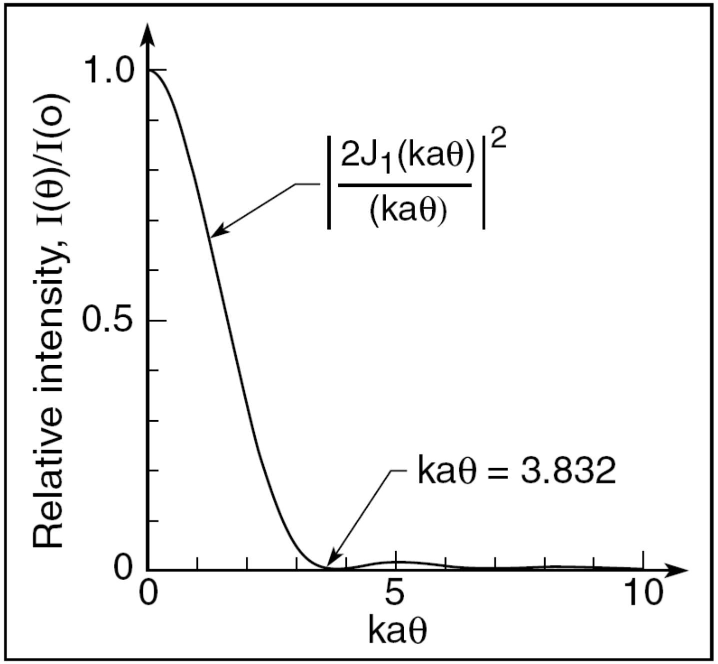
$$\mathbf{B} = \frac{\mathbf{P}}{\Delta \mathbf{A_s} \cdot \Delta \mathbf{\Omega_s}}$$

At the focus, available flux ~ B * δ^2 * NA^2 * η where δ is the spot size and η is the efficiency of the optics, hence the importance of high brightness source and large N.A. optics

Diffraction from a Circular Aperture



Airy pattern



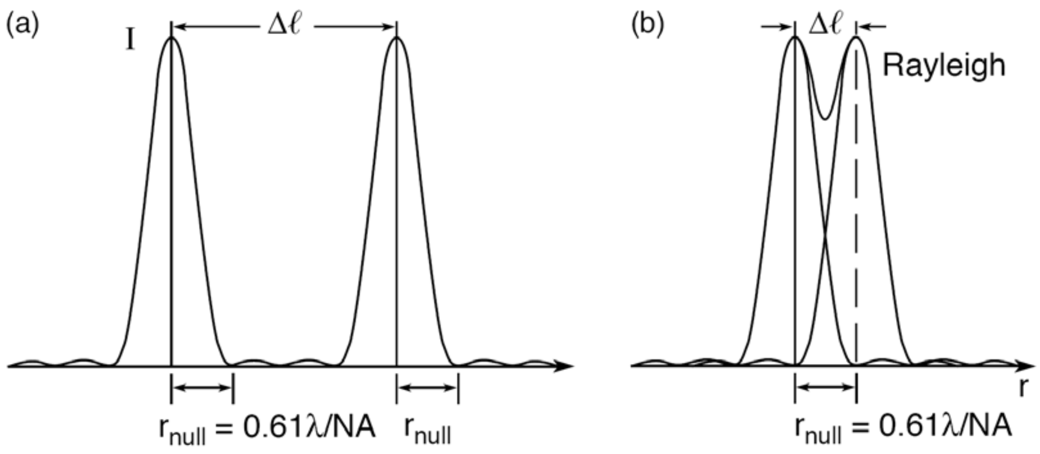
$$ka\theta = 3.822$$

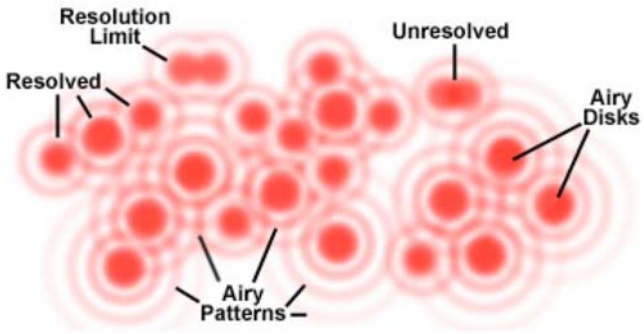
$$\frac{2\pi}{\lambda} a \frac{r_{null}}{z} = 3.822$$

$$r_{null} \cong 0.61 \frac{f}{a} \lambda = 0.61 \frac{\lambda}{NA}$$

D. Attwood (LBNL)

Rayleigh's Criterion for Resolving Two Point Images





- Point sources are spatially coherent
- Mutually incoherent
- Intensities add
- Rayleigh criterion (26.5% dip)

Conclusion: With spatially coherent illumination, objects are "just resolvable" when

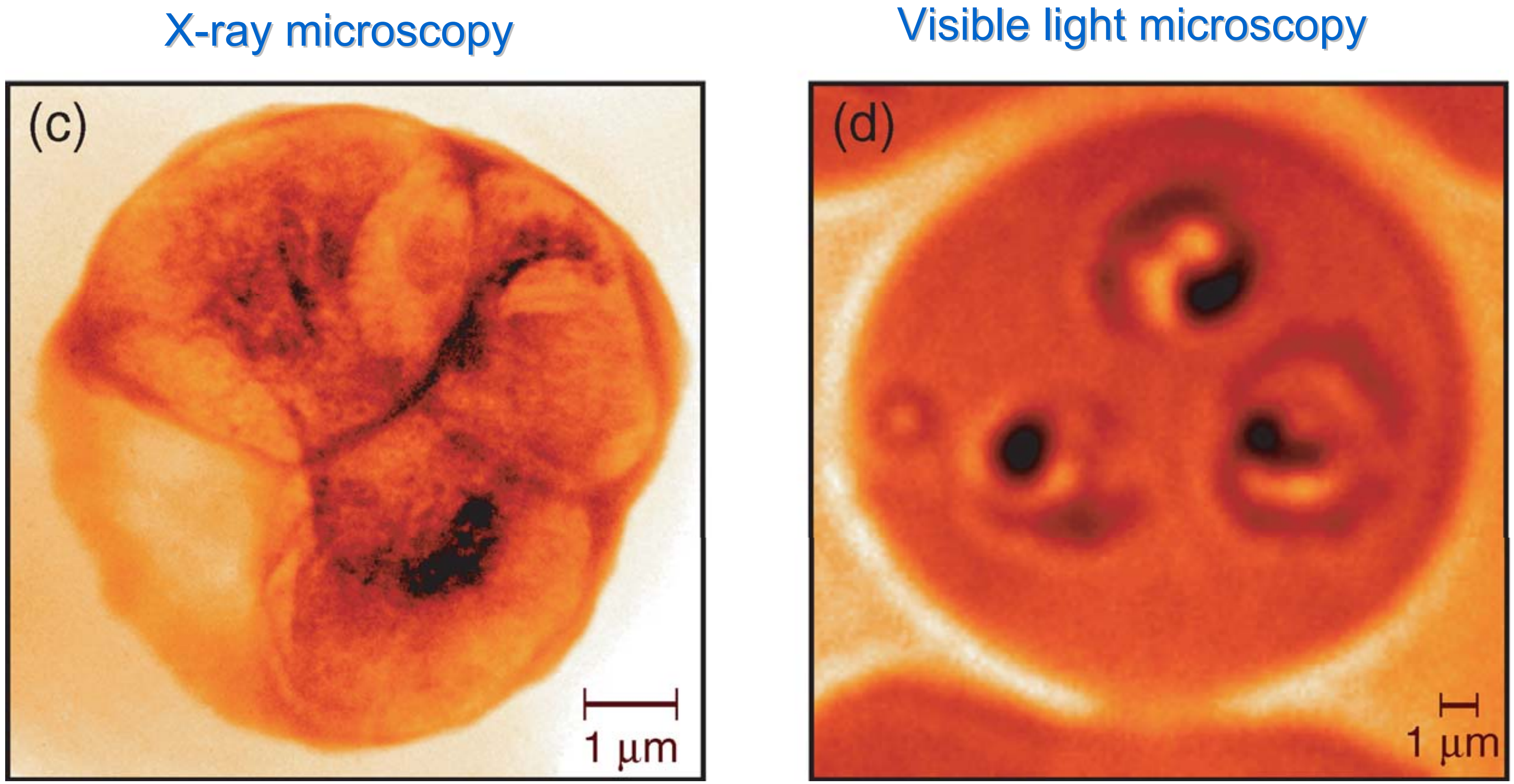
$$\text{Res}|_{coh} = \frac{0.61\,\lambda}{\text{NA}}$$

<= Diffraction limited resolution

D. Attwood (LBNL)

Resolution improves with smaller λ

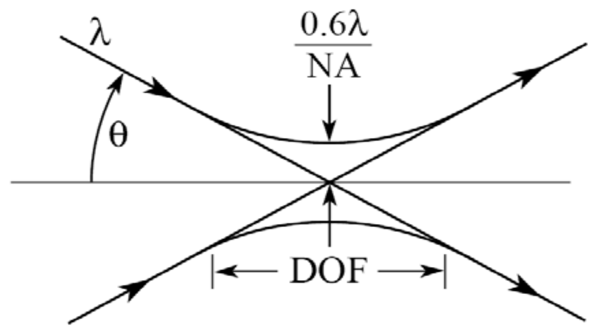
- Malaria-infected red blood cell



C. Magowan, W. Meyer-Ilse, and J. Brown (LBNL)

Depth of Focus

- $$\text{DOF} = \pm\frac{\lambda}{2(\text{NA})^2} = \pm\frac{1.34\delta^2}{\lambda}$$



- DOF determines the sample thickness in 2D imaging and the maximum sample volume in 3D tomography. DOF increases with energy:

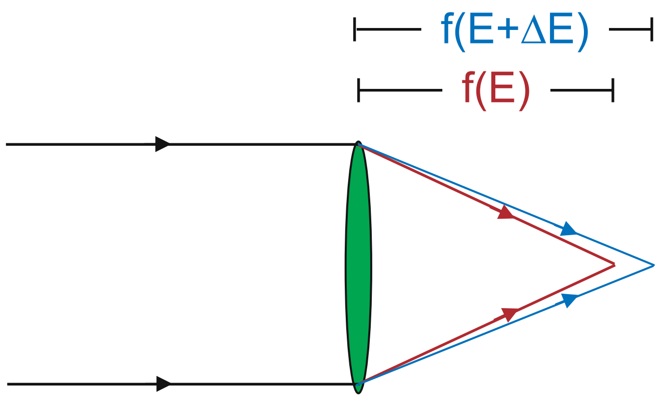
Soft X-rays | ← Hard X-rays → |

Wavelength, λ(A)	23.8 A		4.52 A (Rh)		2.29 A (Cr)		1.54 A (Cu)	
Energy, E	520 eV		2.7 KeV (L)		5.4 KeV (Ka)		8.0 KeV (Ka)	
Resolution, δ, nm	**30**	**60**	**30**	**60**	**30**	**60**	**30**	**60**
DOF (μm)	±1	±4	±5	±21	±10	±42	±16	±63
Si Transmission (%) at 0.5*DOF thickness	**12%**	**0.02 %**	**20%**	**0.18%**	**63%**	**15%**	**80%**	**41%**

W. Yun (Xradia)

Chromatic aberration

- Does focal length depends on λ?
  - Reflective optics: achromatic, can focus white beam, higher flux
  - Diffractive optics: f ~ E
  - Refractive optics: f ~ E^2



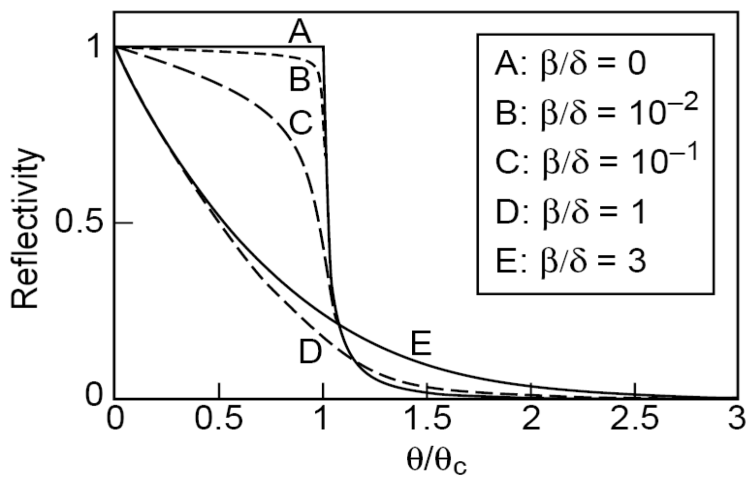
X-ray Microfocusing Optics

- Reflective optics
- Diffractive optics
- Refractive optics

Reflective Optics

- Schwarzschild objective
- Wolter microscope
- Capillary optics
- Kirkpatrick-Baez mirrors

Reflectivity of single and multi-layer



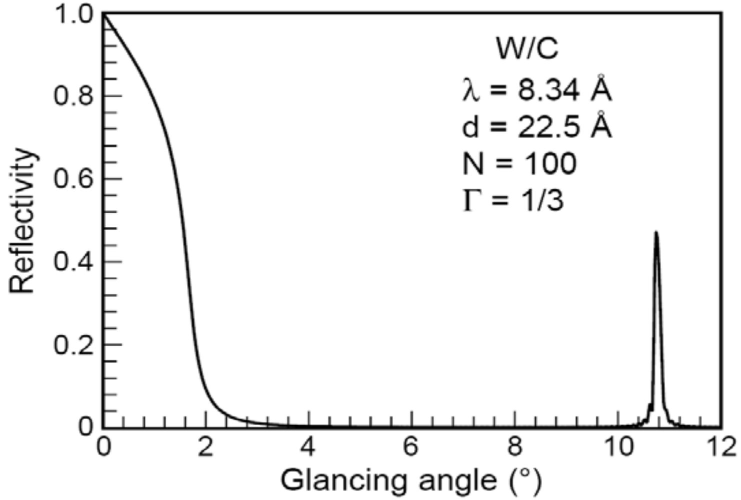
Single layer

- Total external reflection when $\theta<\theta_c$ (~ a few mrad):

$$\theta_c = \sqrt{2\delta} \propto \lambda\sqrt{Z}$$

$$n = 1-\delta+i\beta$$

- Finite β/δ rounds the reflectivity curve

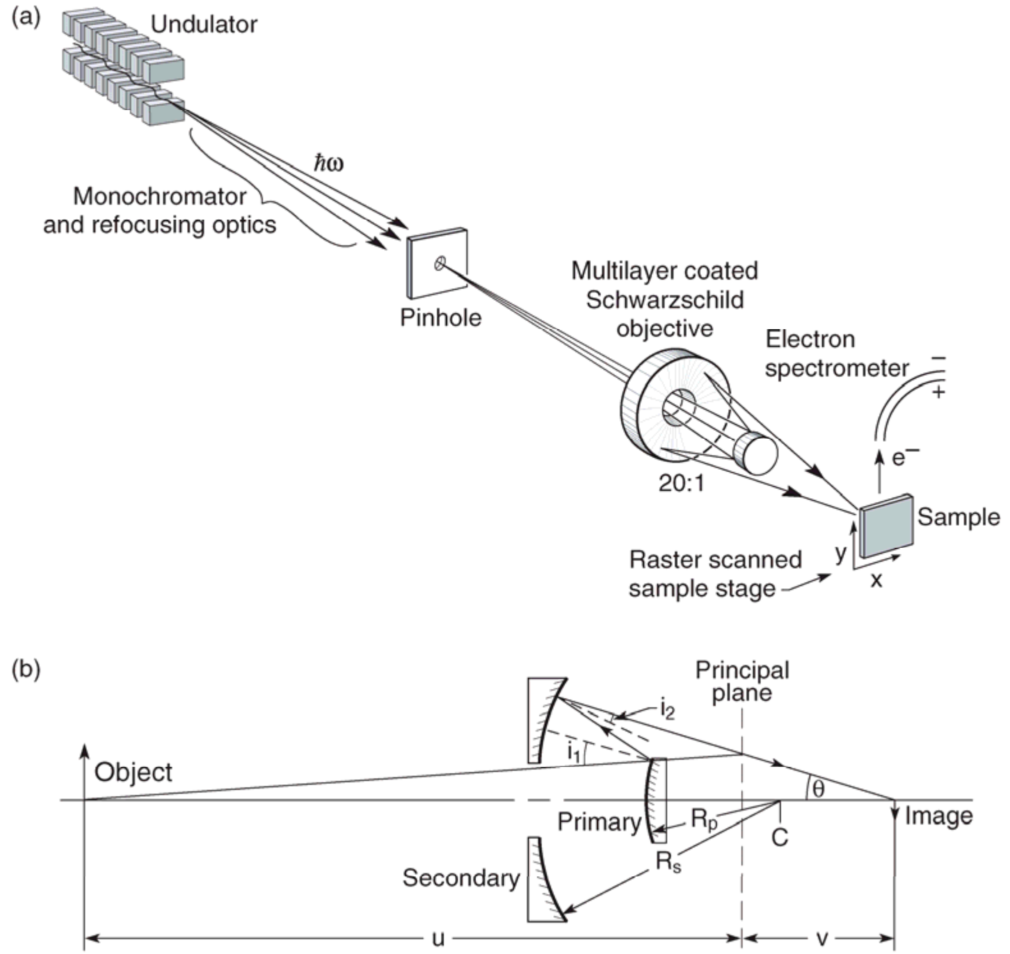


Multilayers

- Large θ means shorter mirror or larger acceptance
- Spectral bandwidth ~ a few %.
- Cannot focus white beam

Schwarzschild Objective

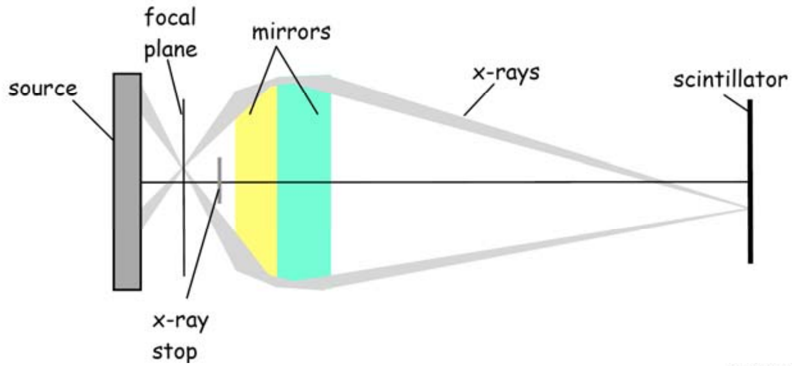
- Near normal incidence with multilayer coating (126 eV)
- N.A. > 0.1
- Imaging microscope

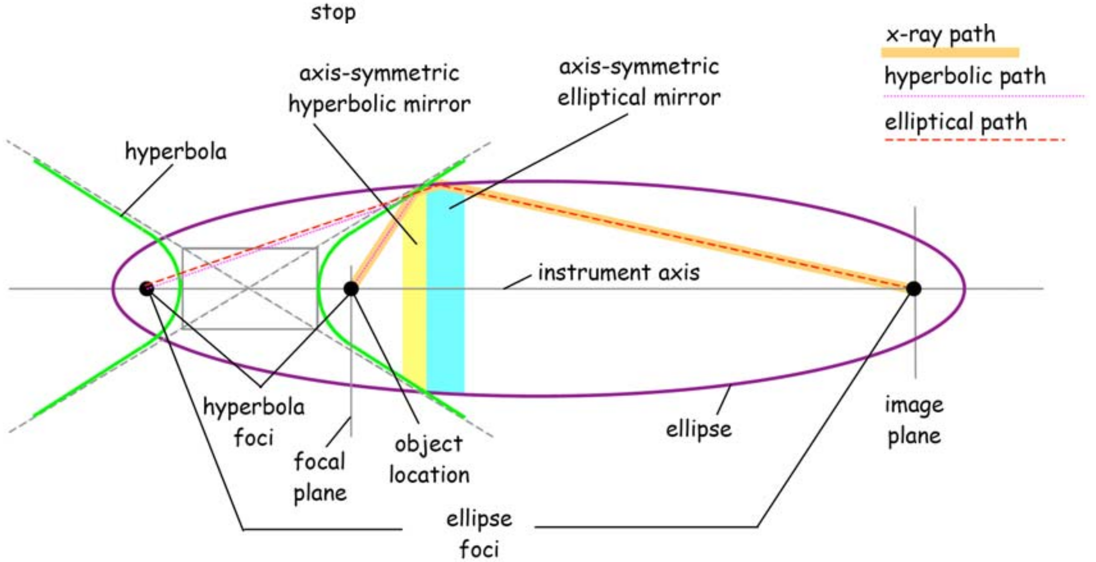


F. Cerrina (UW-Madison), J. Underwood (LBNL)

Wolter Type I Microscope

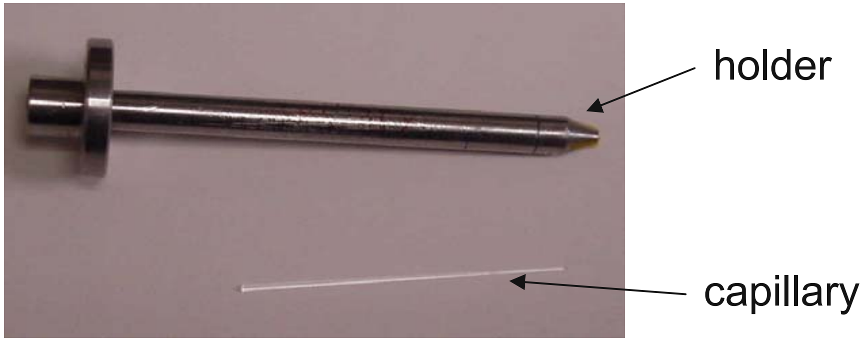
- Use 2 coaxial conical mirrors with hyperbolic and elliptical profile
- Imaging microscope
- Difficult to polish for the right figures and roughness

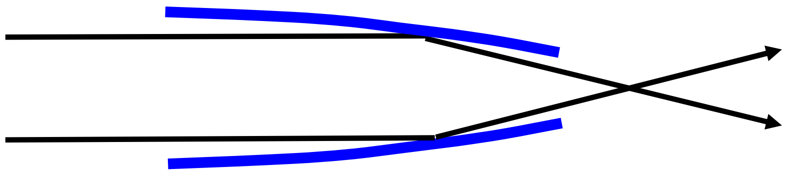




J.A. Jackson (LLNL)

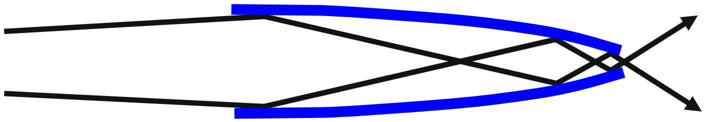
Glass capillary optics





One-bounce capillary

- Large working distance (cm)
- Compact: may fit into space too small for K-B
- Nearly 100% transmission
- N.A. ~ 2-4 mrad ($\leq 2\theta_c$)
- Difficult to make submicron spot

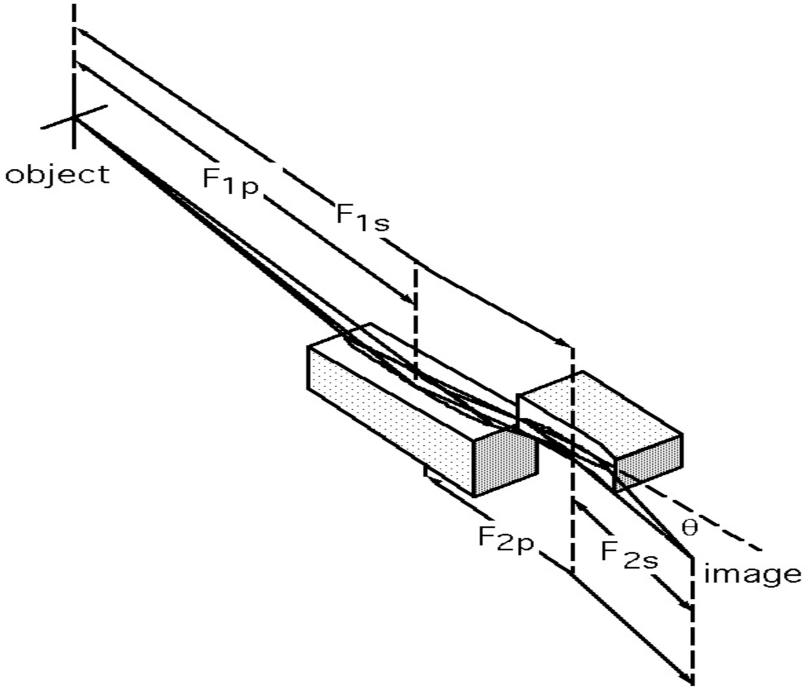


Multi-bounce condensing capillary

- Easy to make with small opening (submicron)
- Short working distance (100 μm)
- Low transmission

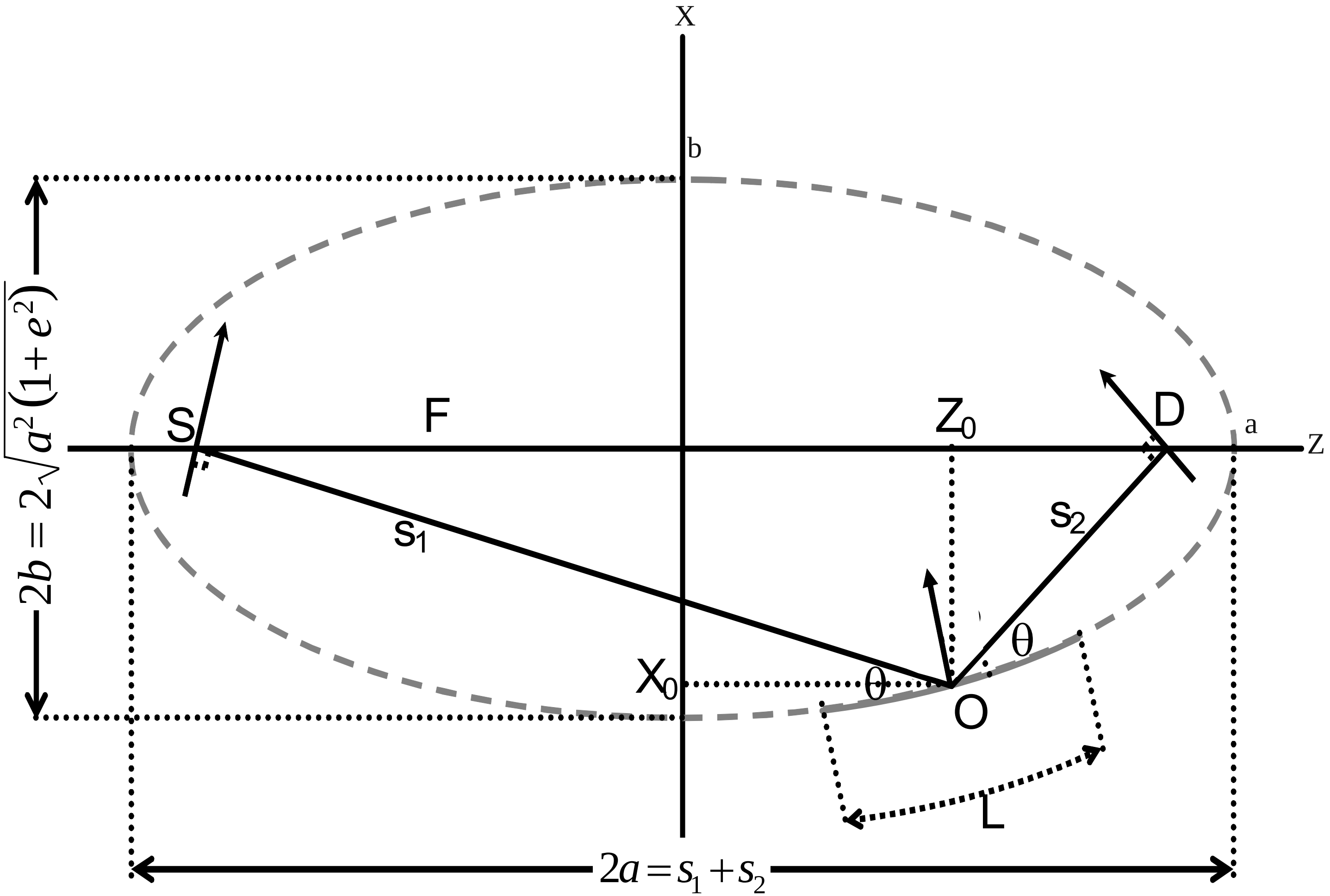
D. Bilderback (Cornell)

Kirkpatrick-Baez mirrors pair



- A horizontal and a vertical mirror arranged to have a common focus
- Achromatic: can focus pink beam (but not with multilayer coating)
- Different focal lengths and demagnifications: can be used to produce ~ round focal spot
- Very popular for focusing in the 1-10 μm regime: relatively easy to make, longer mirrors can be used for higher flux
- For submicron focusing, mirrors with precise elliptical profile are required (figure error < 1 μrad)

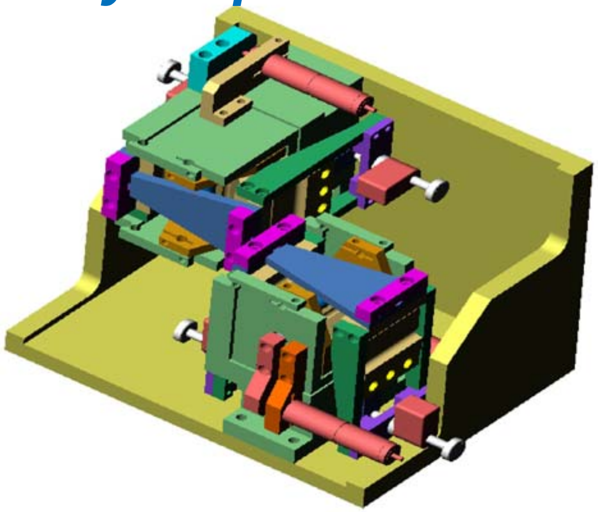
Elliptical x-ray mirrors



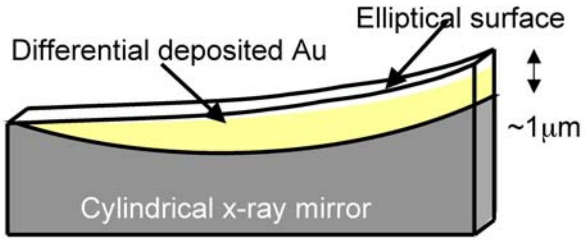
A. Macrander (APS)

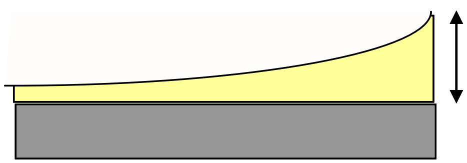
Methods used for making x-ray quality elliptical mirrors

- **Bending**
  - **ALS**
  - **ESRF**

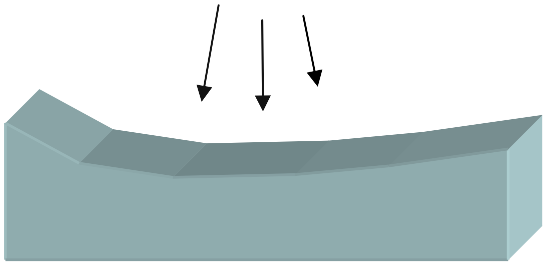


- **Differential deposition/profile coating**
  - **APS (C. Liu)**





- **Differential polishing**
  - **Osaka/Spring8**
  - **APS/Tinsley**



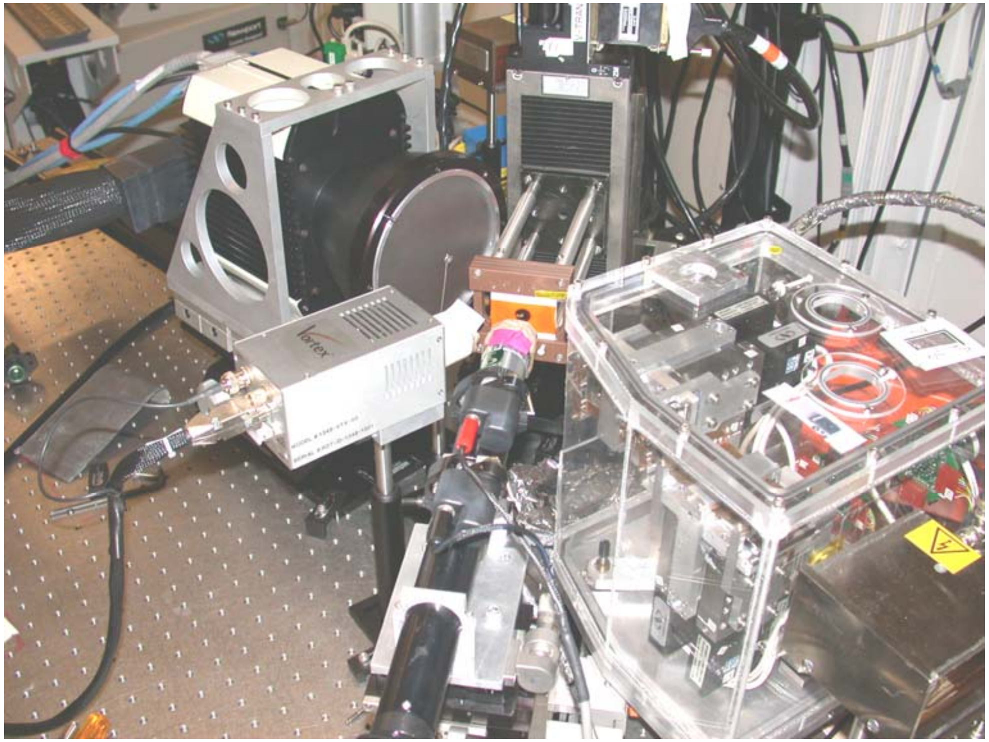
G. Ice (ORNL)

K-B mirrors are very popular for micron scale focusing

- At the APS, K-B microprobes with 100 and 200-mm long bent mirrors are common:
  - MR-CAT 10-ID
    (J. Kropf, K. Kemner)
  - GSECARS 13-ID-C
    (S. Sutton, M. Rivers)
  - BioCAT 18-ID
    (T. Irving, R. Barrea)
  - PNC/XOR 20-ID
    (S. Heald, D. Brewe)

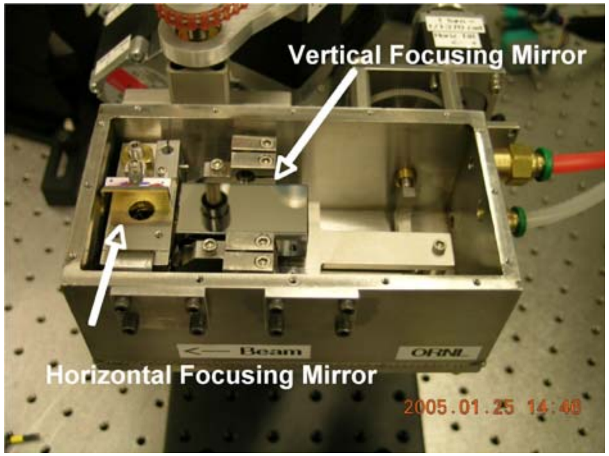
- Monochromatic flux ~ 10^{11}–10^{12} ph/sec

GSECARS microprobe



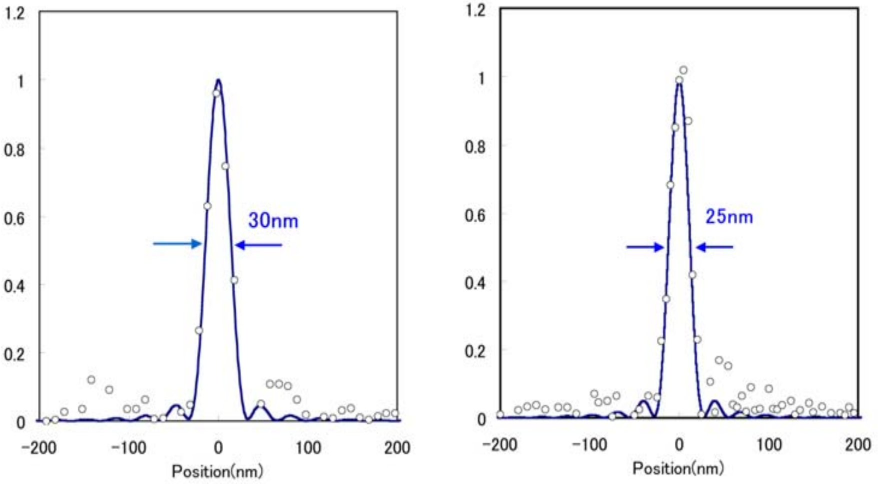
KB mirror systems for nanofocusing

APS/ORNL 34-ID



- APS/ORNL collaboration KB optics
  - Poly/mono Beams 85 x 95 nm
- ESRF 45 nm
- Osaka/Spring-8 ~ 25 nm x30 nm
- Simple KB system diffraction limit ~17 nm

Osaka mirrors

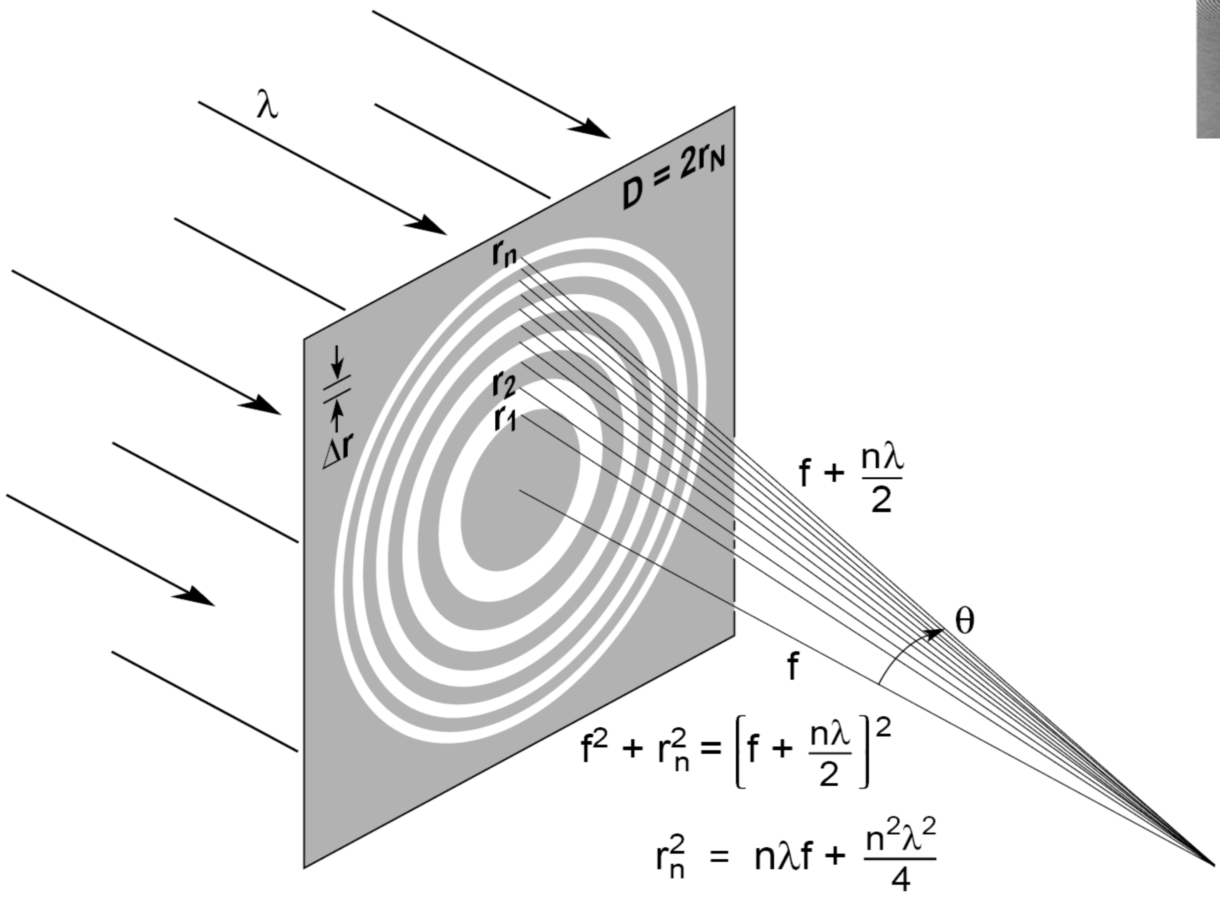


G. Ice (ORNL)

Diffractive Optics

- Fresnel zone plates (FZP)
- Multilayer Laue Lens (MLL)

Fresnel zone plates: basic formula



$$f^2 + r_n^2 = \left(f + \frac{n\lambda}{2}\right)^2$$

$$r_n \approx \sqrt{nf\lambda}$$

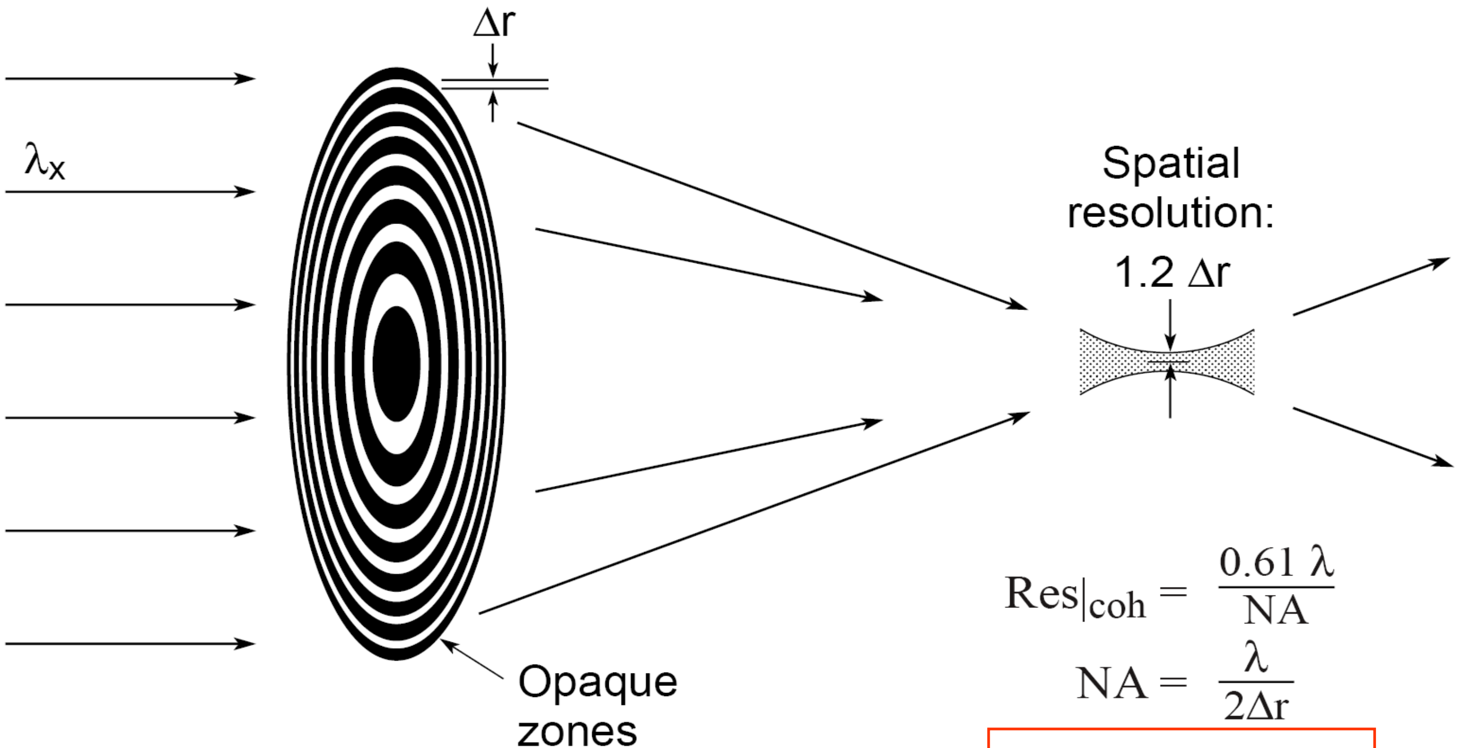
$$2r_n\Delta r = f\lambda$$

$$\#\text{ of zones} = \frac{r}{2\Delta r}$$

$$NA = \frac{\lambda}{2\Delta r}$$

D. Attwood (LBNL)

Diffraction limited resolution



$$\mathrm{Res}|_{coh} = \frac{0.61\,\lambda}{NA}$$

$$NA = \frac{\lambda}{2\Delta r}$$

$$\therefore\ \boxed{\mathrm{Res}|_{coh} = 1.22\,\Delta r}$$

Coherent illumination

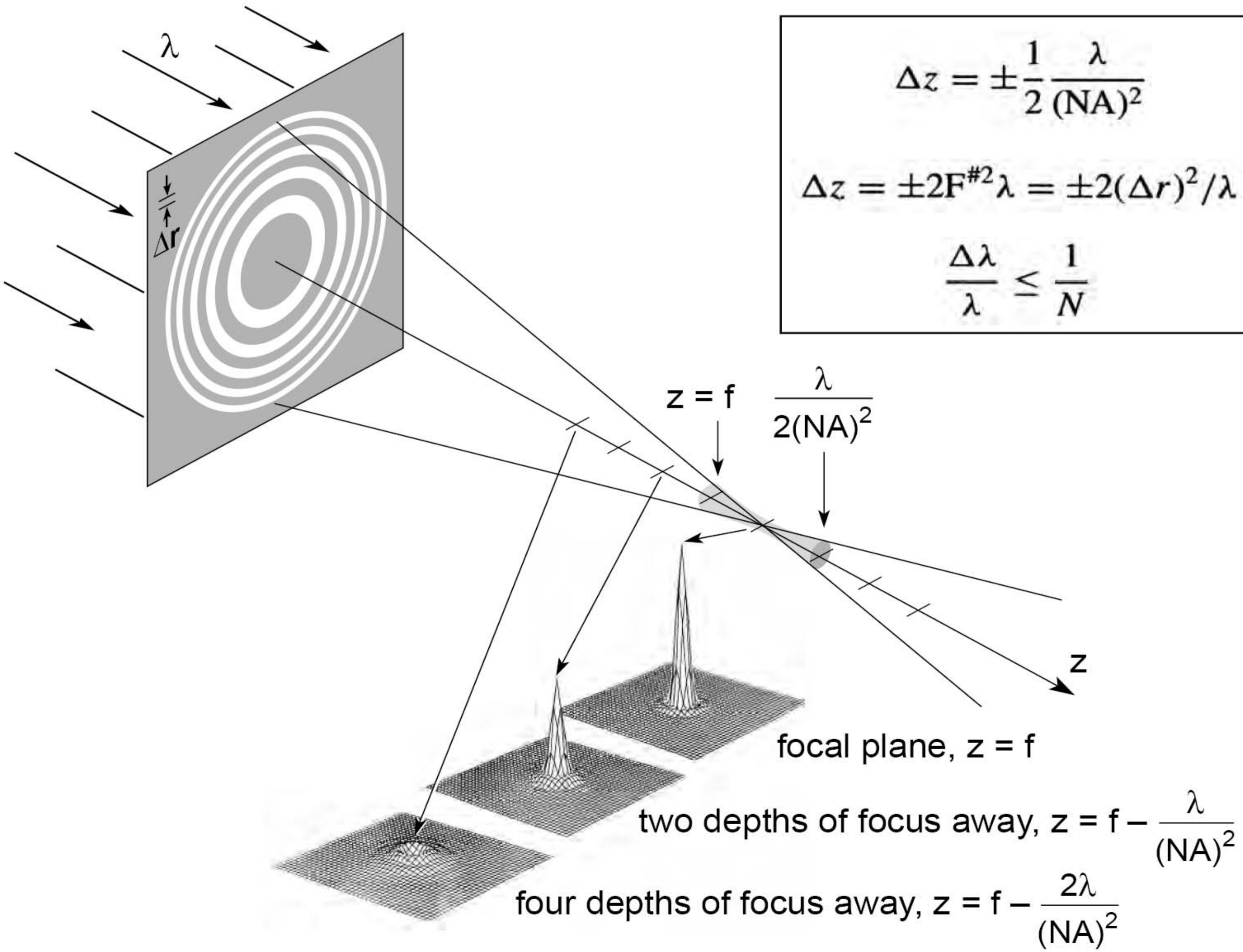
D. Attwood (LBNL)

Depth of focus and spectral bandwidth

$$\Delta z = \pm \frac{1}{2} \frac{\lambda}{(\mathrm{NA})^2}$$

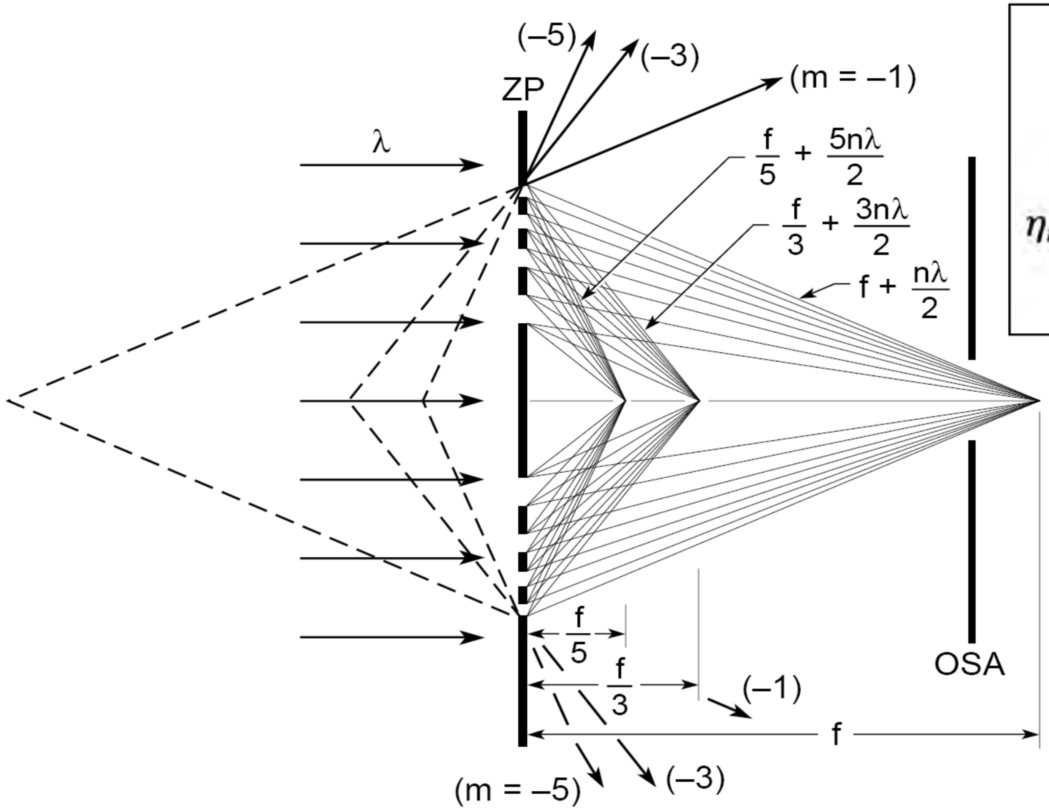
$$\Delta z = \pm 2 F^{\#2} \lambda = \pm 2 (\Delta r)^2 / \lambda$$

$$\frac{\Delta \lambda}{\lambda} \leq \frac{1}{N}$$



D. Attwood (LBNL)

Higher orders and negative orders



$$r_n^2 \simeq mn\lambda f_m$$

$$\eta_m = \begin{cases} \frac{1}{4} & m = 0 \\ 1/m^2\pi^2 & m \text{ odd} \\ 0 & m \text{ even} \end{cases}$$

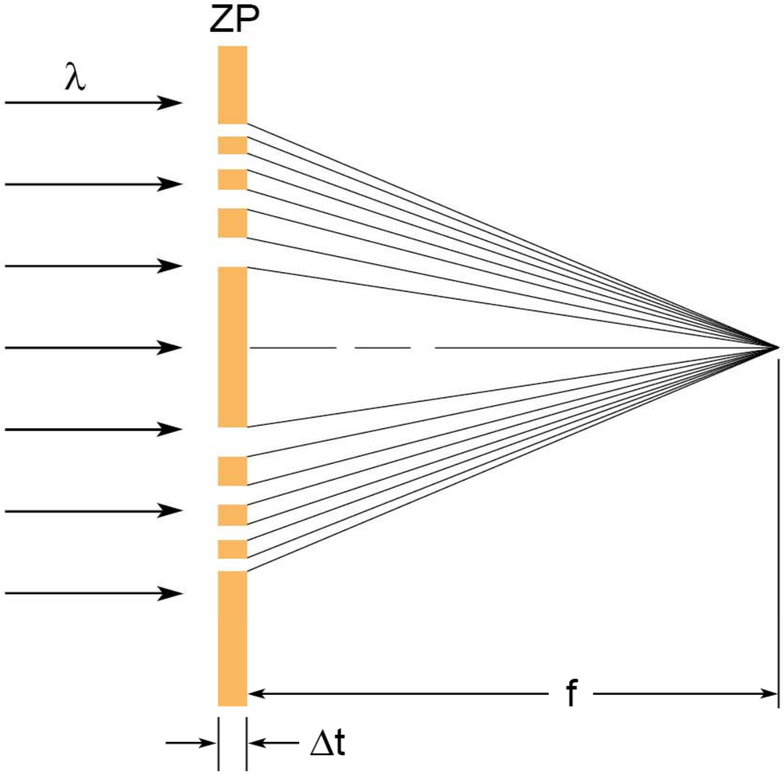
$$f_m = \frac{1}{m} \frac{r_N^2}{N\lambda}$$

$$f_m = \frac{1}{m} f_1$$

D. Attwood (LBNL)

Efficiency: Phase vs Amplitude Zone Plates

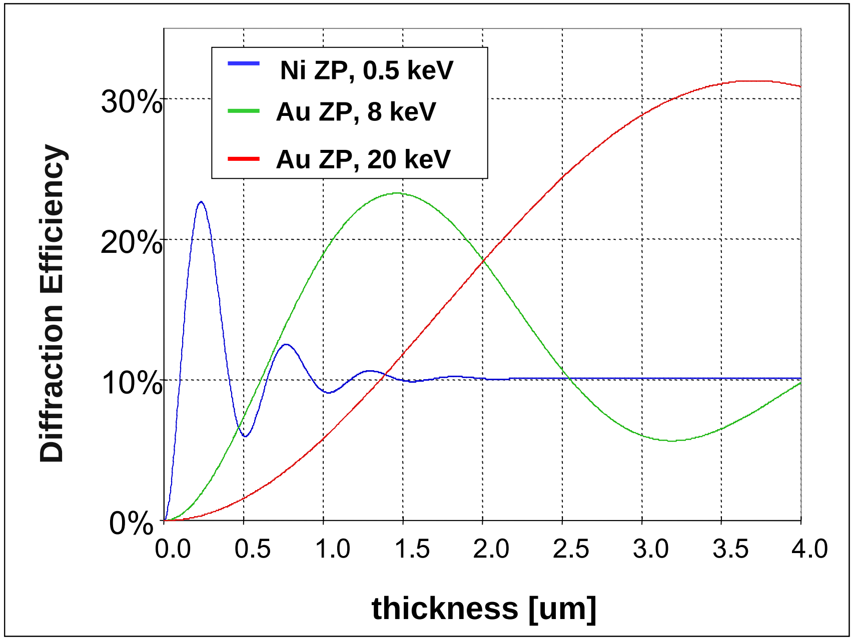
- Efficiency of an **amplitude** ZP with opaque zones ~ 10%
- Efficiency of a **phase** ZP with π-phase shift ~ 40%



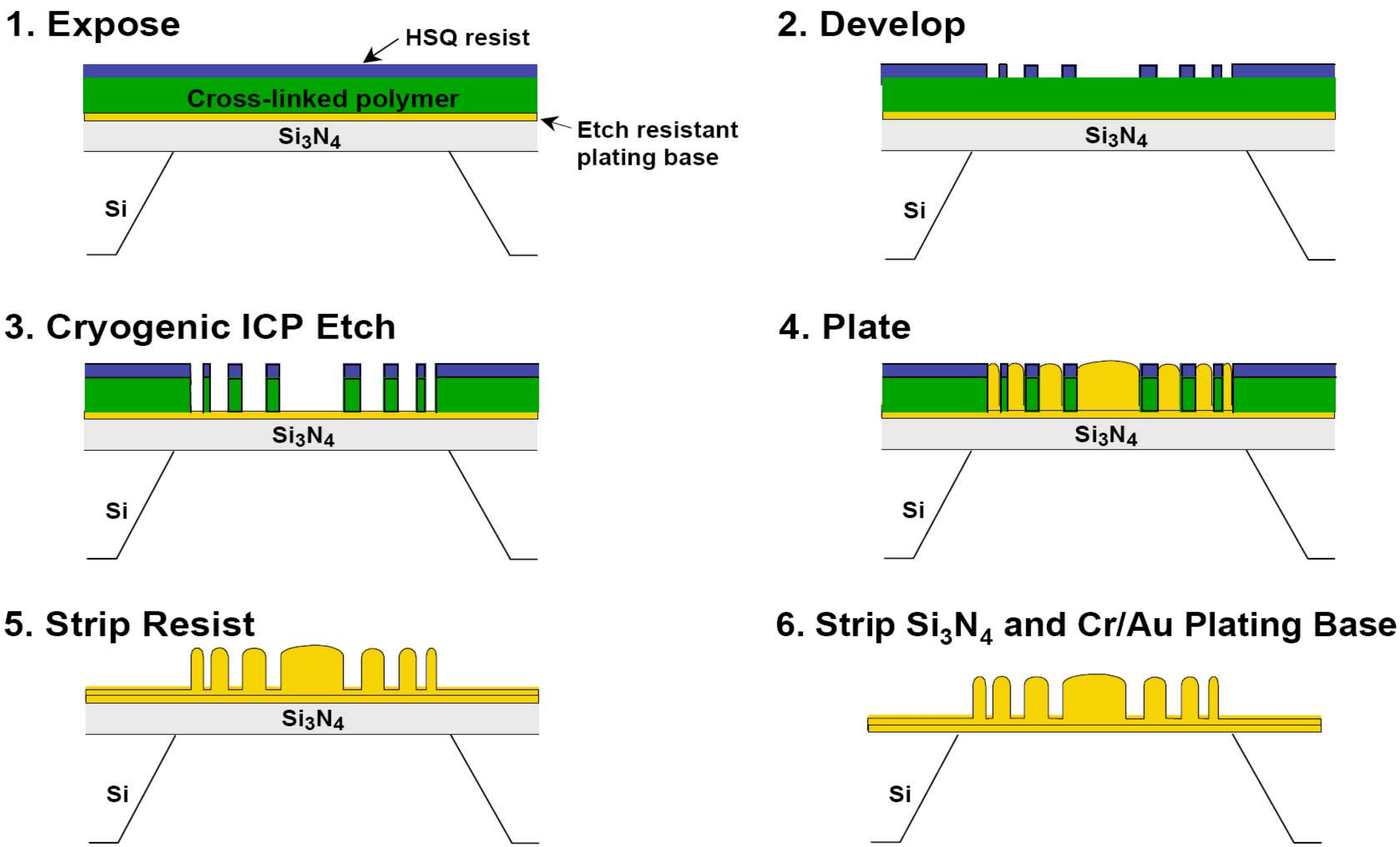
$$\Delta\phi = \left(\frac{2\pi\delta}{\lambda}\right)\Delta t$$

For a π-phase shift

$$\Delta t = \frac{\lambda}{2\delta}$$



Fabrication of FZP



E-beam Lithography

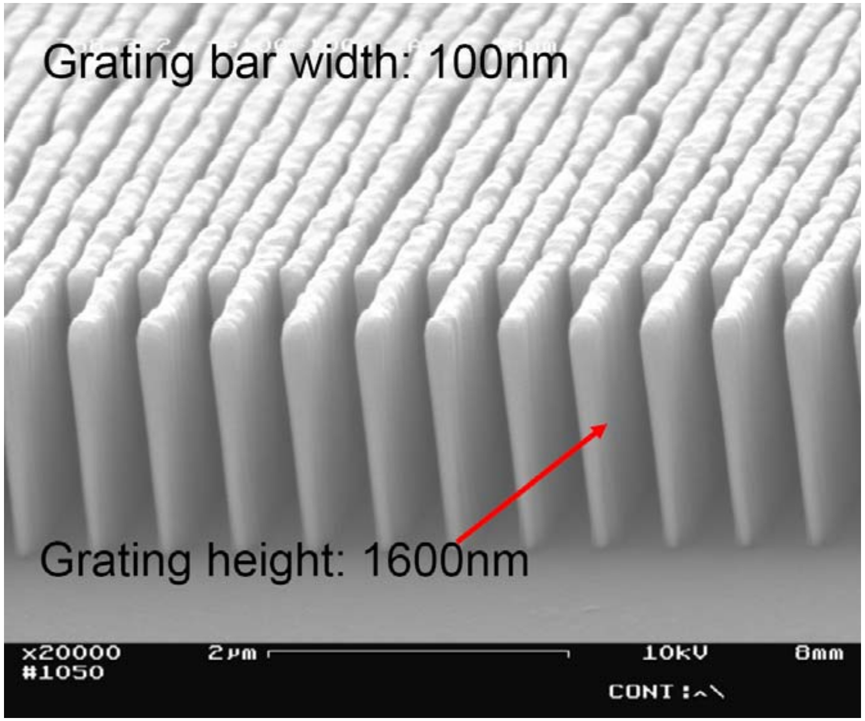
Pattern Transfer

Electro-plating

Courtesy of E. Anderson, A. Liddle, W. Chao, D. Olynick, and B. Harteneck (LBNL)

Recent Hard X-ray Zone Plates

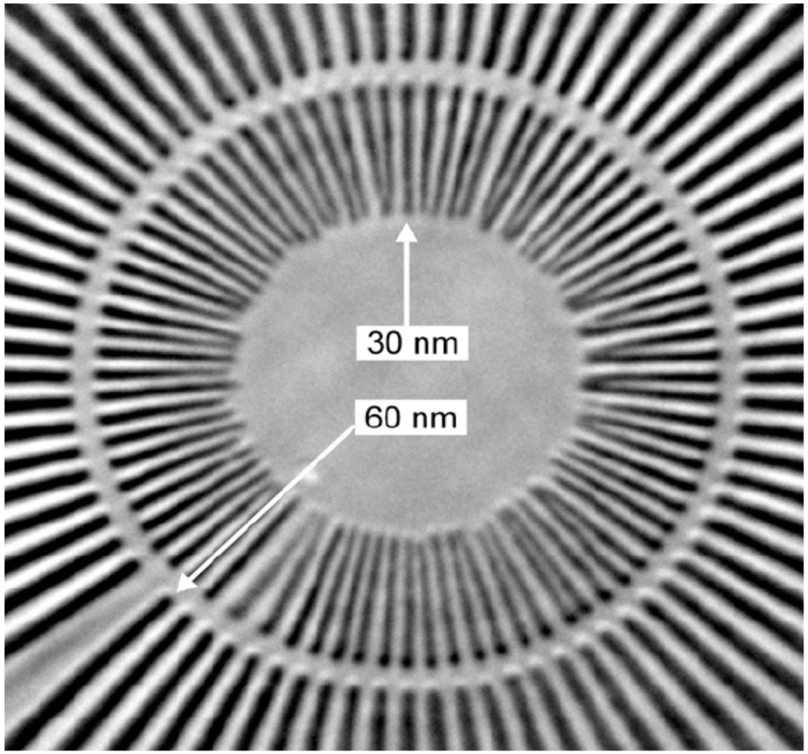
- Δr = 30 nm, 450 nm thick, AR = 15 (Academia Sinica)
- Δr = 24 nm, 300 nm thick, AR = 12.5 (Xradia)
- To achieve good efficiency, aspect ratio needs to be increased (e.g. needs 1.5 μm thick for optimal efficiency at 8 keV)



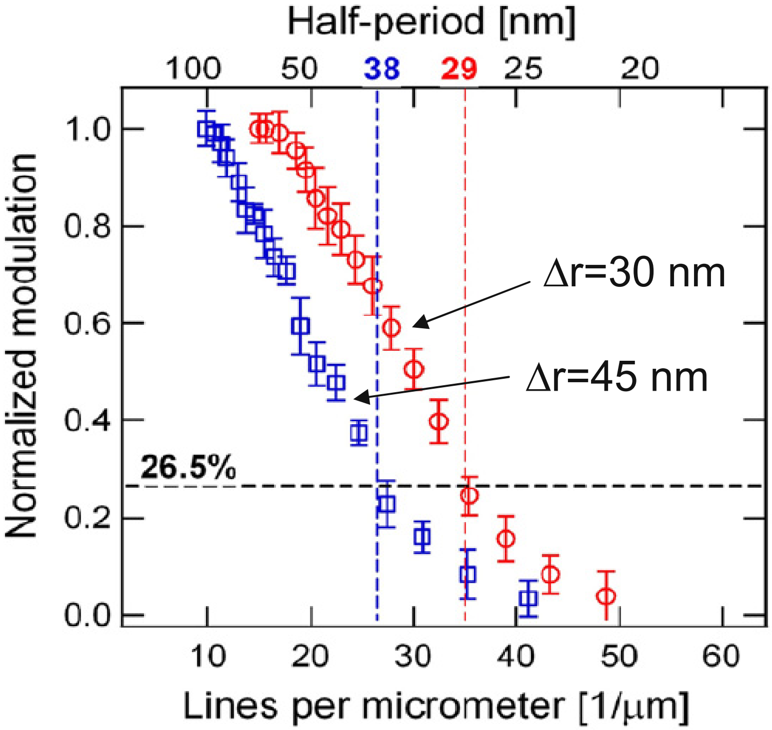
W. Yun (Xradia)

Recent Images from TXM at 32-ID

Image of a Au test pattern at 8 keV



Modulation Transfer Function (MTF)

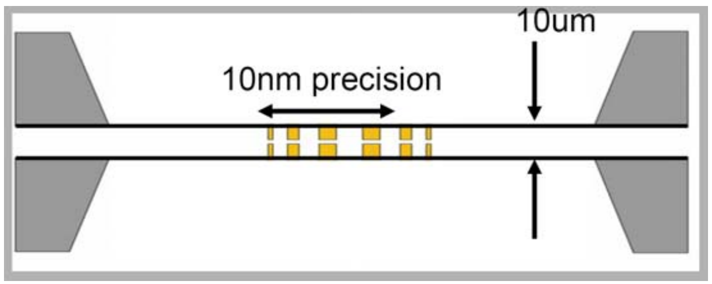


Y-T. Chen *et al*., Nanotech. **19**, 395302 (2008).

Other means to increase the aspect ratio

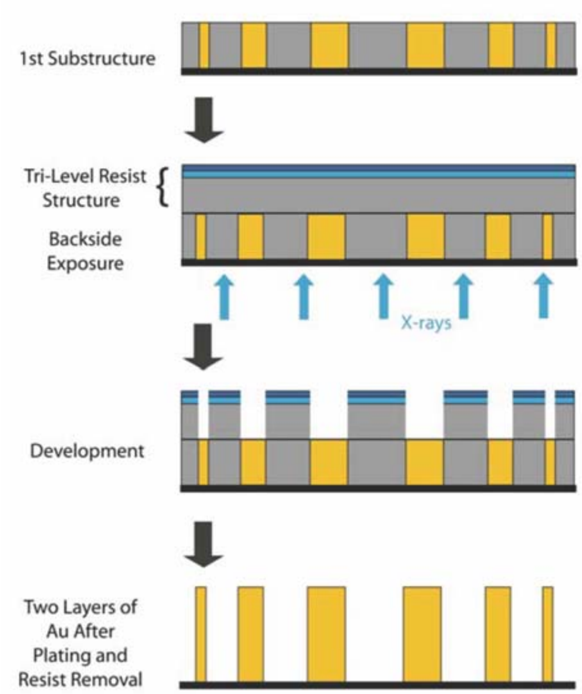
Align and bond two ZPs within DOF

- Lateral alignment tolerance ~ $\Delta r/3$ (10 nm for 30-nm ZP)
- < 10 μm separation between the ZPs



Use the first ZP as self-aligning mask

- 100 nm demonstrated
- Photoresist mechanical and stress issue



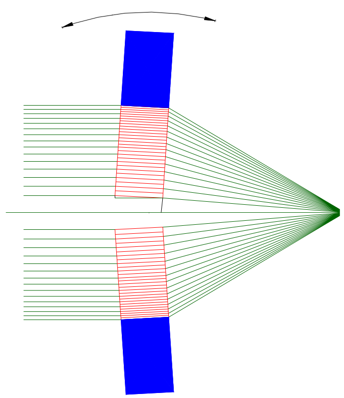
W. Yun (Xradia)

Even with stacking, aspect ratio > 100 is probably difficult to achieve with lithographic zone plates!

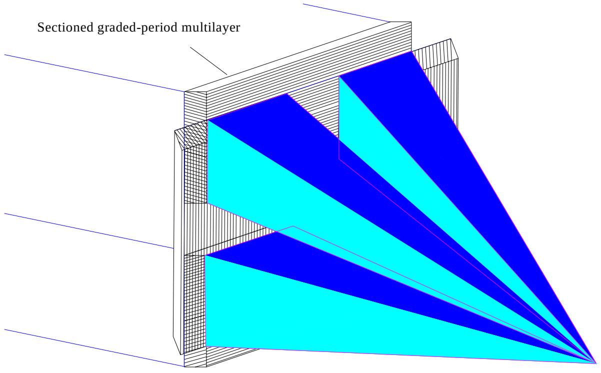
Multilayer Laue Lens: novel approach for high aspect ratio

Varied d-spacing multilayers | Dicing ~ 1mm | Polishing ~ 5-25 μm

1D MLL



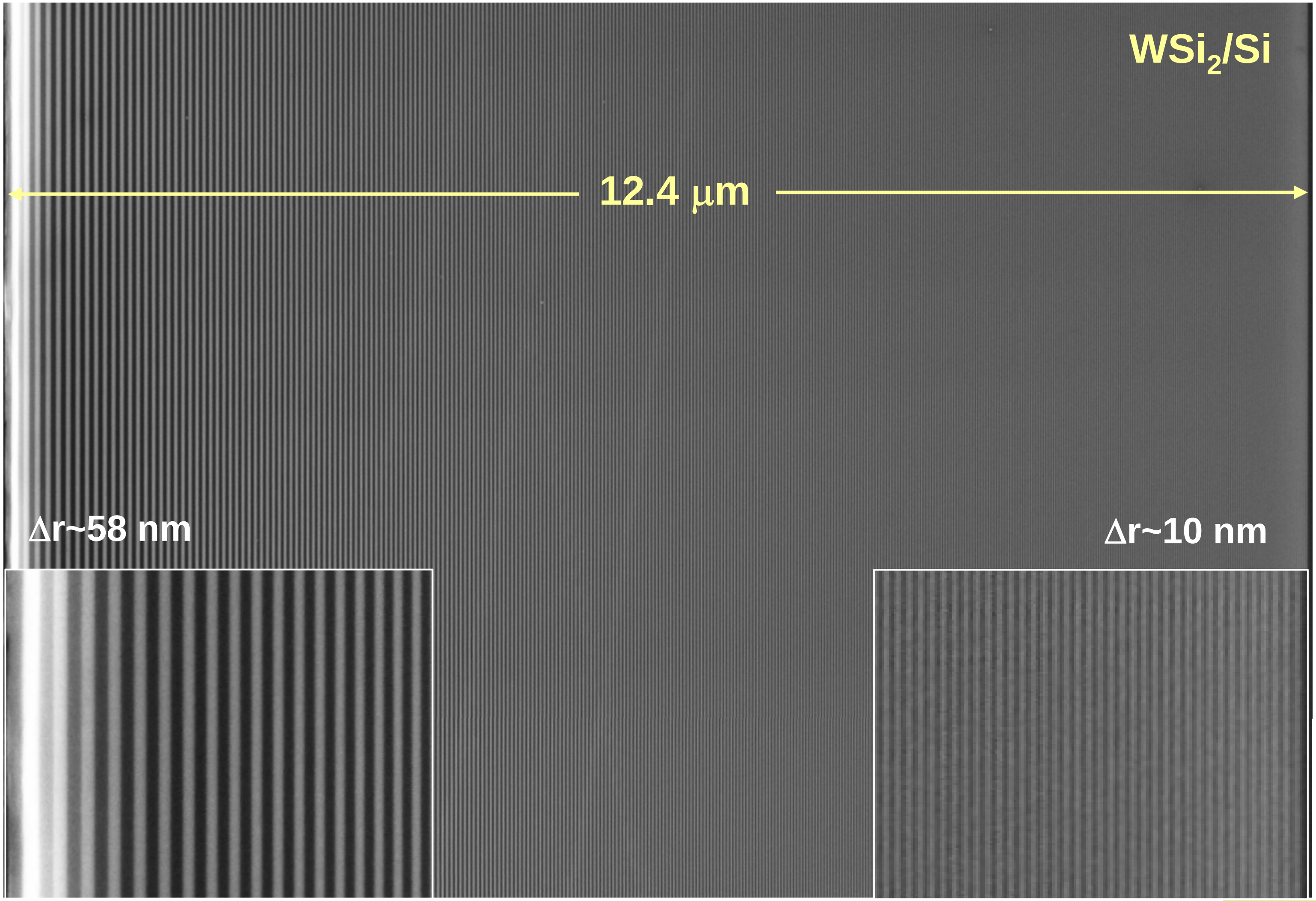
2D MLL



- Aspect ratio > 1000 (Δr = 5-10 nm, 10 μm thick) demonstrated
- Engineering challenge of aligning and assembling 2 or 4 MLLs to produce a single optics

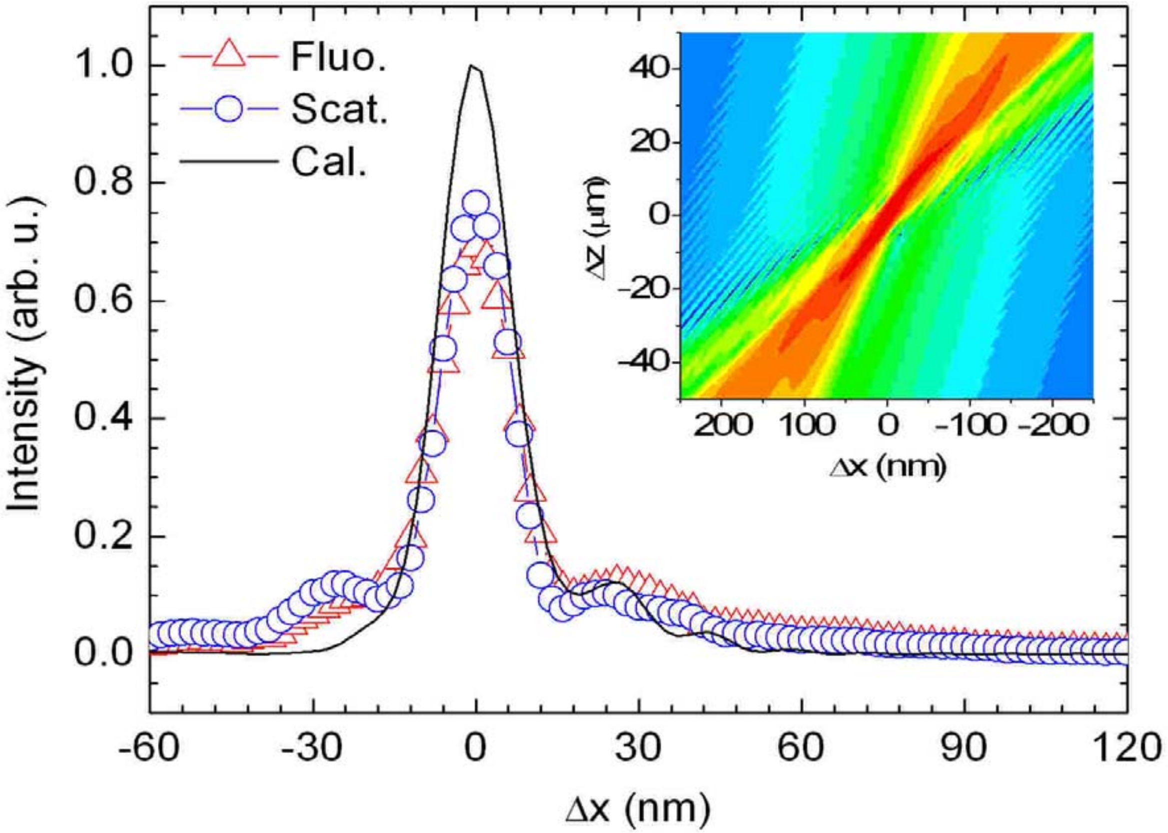
A. Macrander (APS)

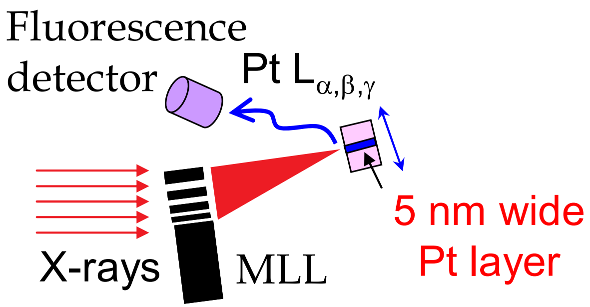
SEM image of an MLL



A. Macrander (APS)

Best measured line focus of MLL



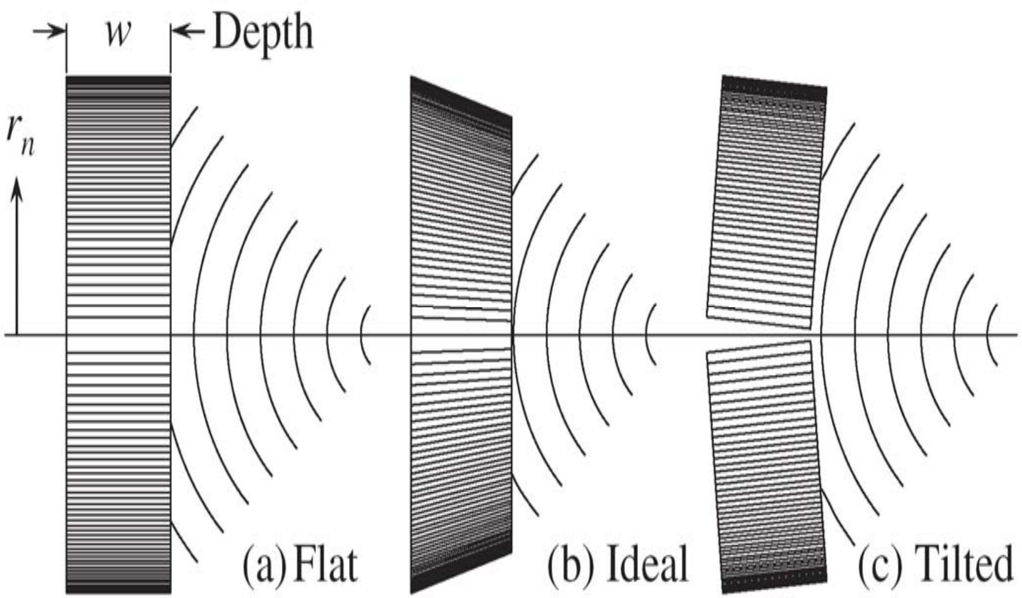


Flou.	17.6 nm
Scatt.	15.6 nm
Cal.	15.0 nm

Efficiency: 31%
Energy: 19.5 keV

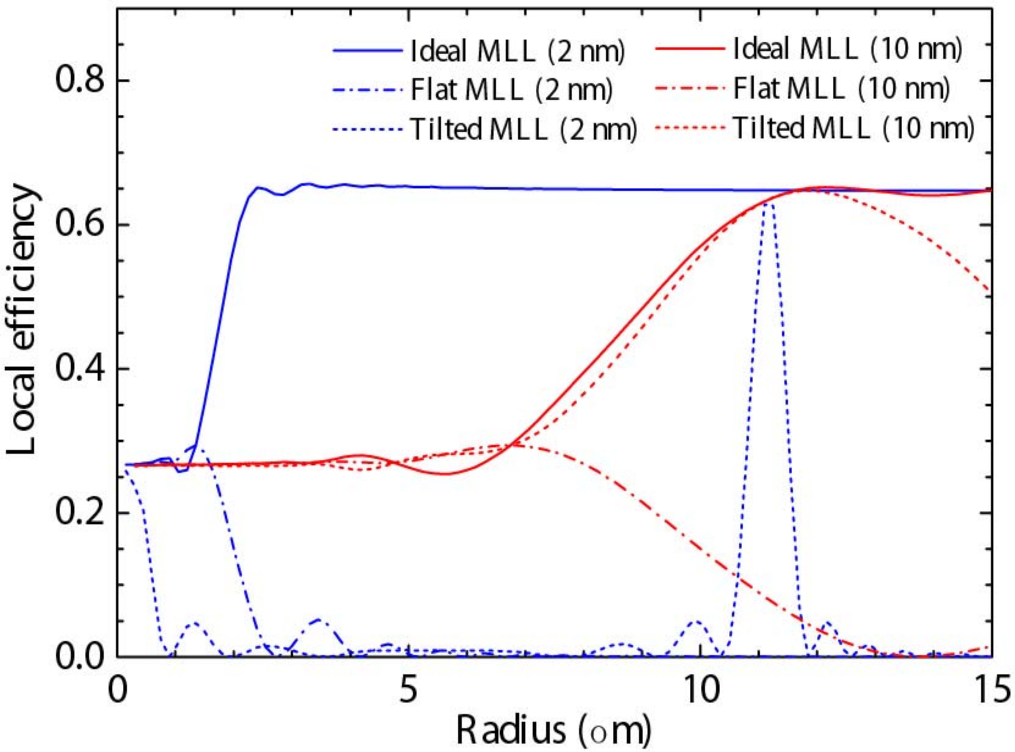
H.C. Kang *et al*., APL **92**, 221114 (2008)

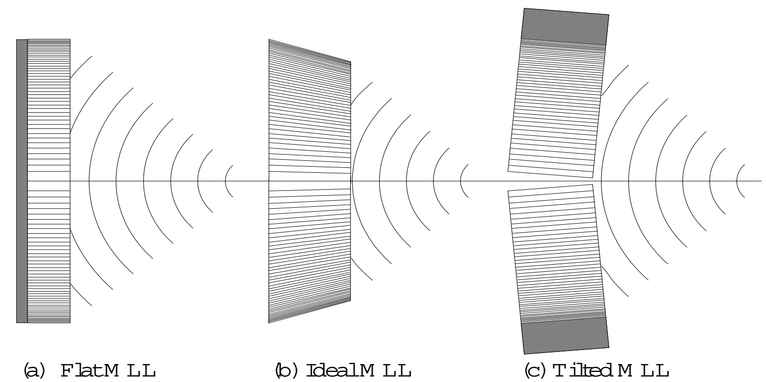
Thin vs Thick Zone Plate



- When aspect ratio increases, effects from dynamical diffraction vs kinematic scattering need to be considered
- Zones should be inclined locally to satisfy Bragg condition
- Thin to thick transition: $w = (2\Delta r)^2/\lambda \sim DOF$

- For flat structure, local efficiency decreases at large r
- For tilted or ideal wedged structures, efficiency actually increases beyond the thin phase ZP limit of 40%
- This effect is enhanced for high resolution (small Δr)





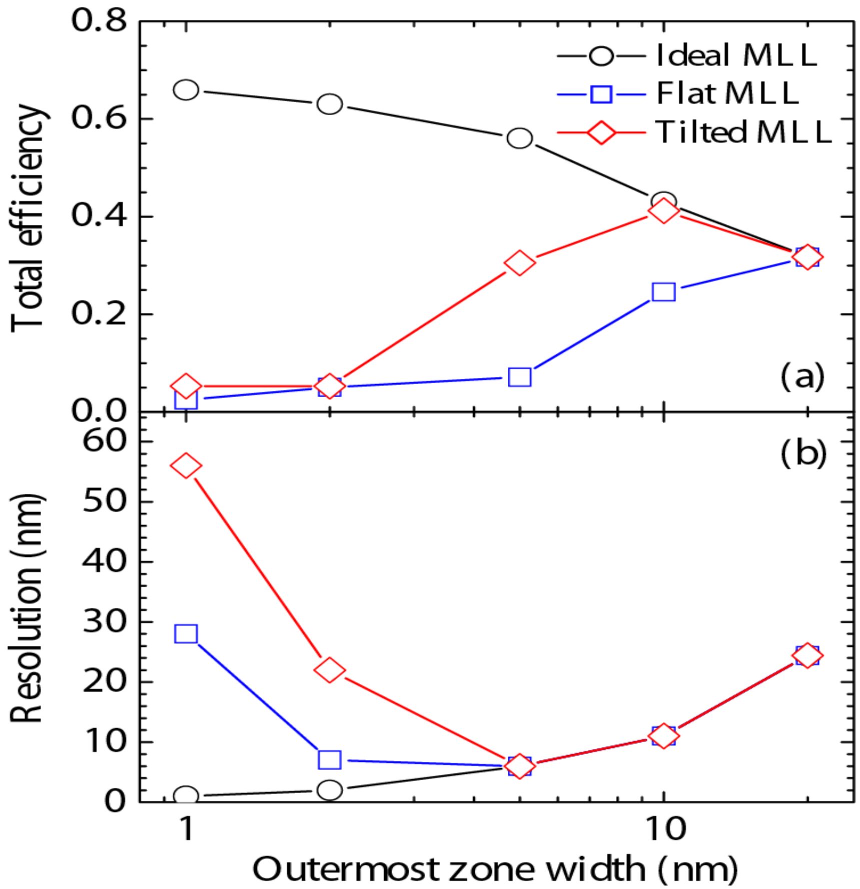
flat

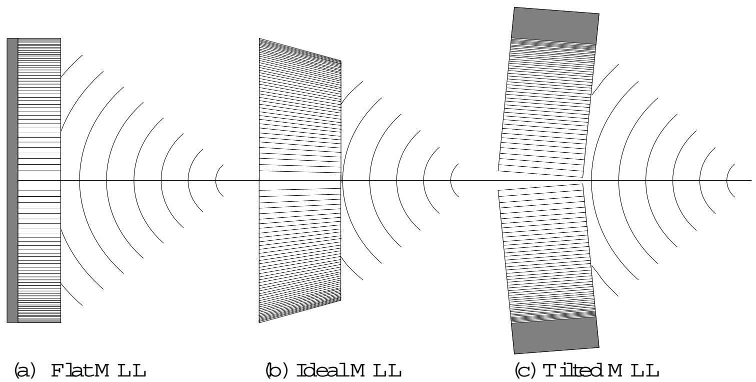
ideal (wedged)

tilted

H.C. Kang *et al*., PRL **96**, 127401 (2006)

- Despite lower overall efficiency, both flat and tilted structure can achieve ~ 5 nm resolution





flat

ideal (wedged)

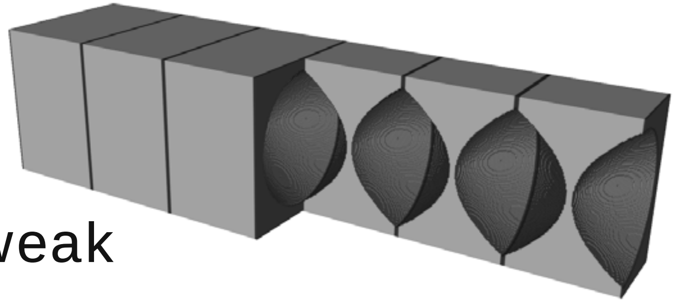
tilted

H.C. Kang *et al*., PRL **96**, 127401 (2006)

Refractive Optics

- Compound refractive lens (CRL)

Refraction & Absorption



Refraction of hard x-rays in matter is weak

$$n = 1 - \delta + i\beta, \quad (\delta \approx 10^{-6} \text{ @20keV})$$

- strong curvature of lens surfaces
- stacking of many lenses behind each other

Absorption of x-rays in lenses reduces the efficiency

- lenses must be made of low *Z* material (Be, B, C, Al, ...)
- lenses should be made as thin as possible

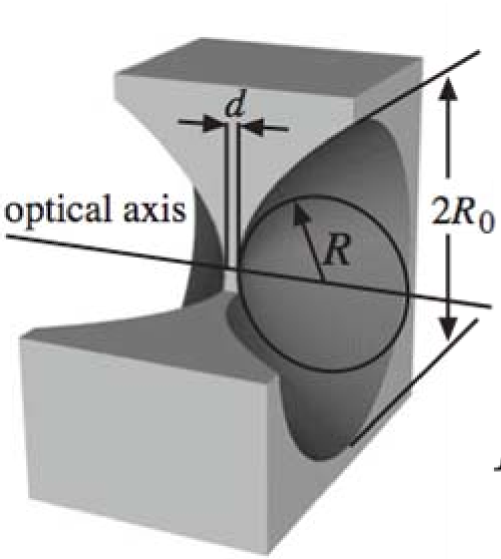
Refractive index *n* smaller than 1:

- focusing lens must be concave

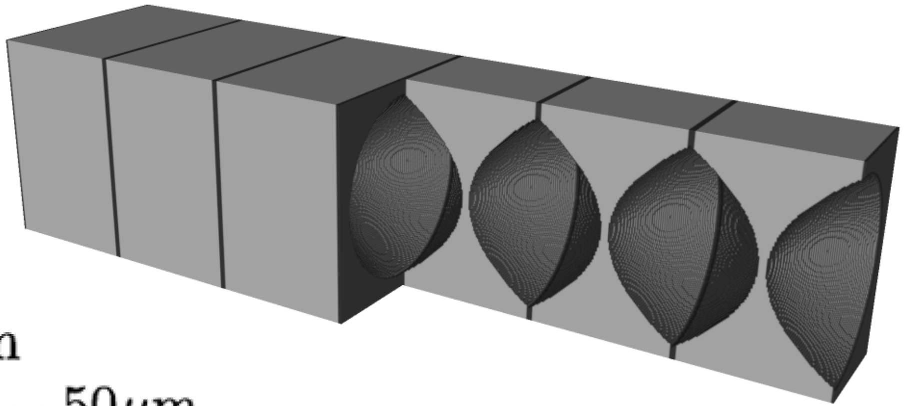
C. Schroer (Tech Univ Dresden)

Parabolic Refractive X-Ray Lenses

single lens



stack of lenses:
compound refractive lens (CRL)



$$R = 200\mu m$$
$$d = 10\mu m - 50\mu m$$
$$2R_0 = 800\mu m - 1000\mu m$$

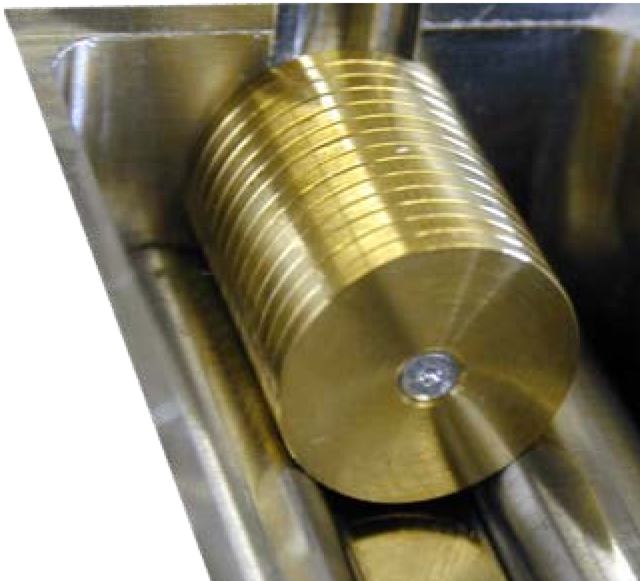
variable number of lenses: *N* = 10 … 300

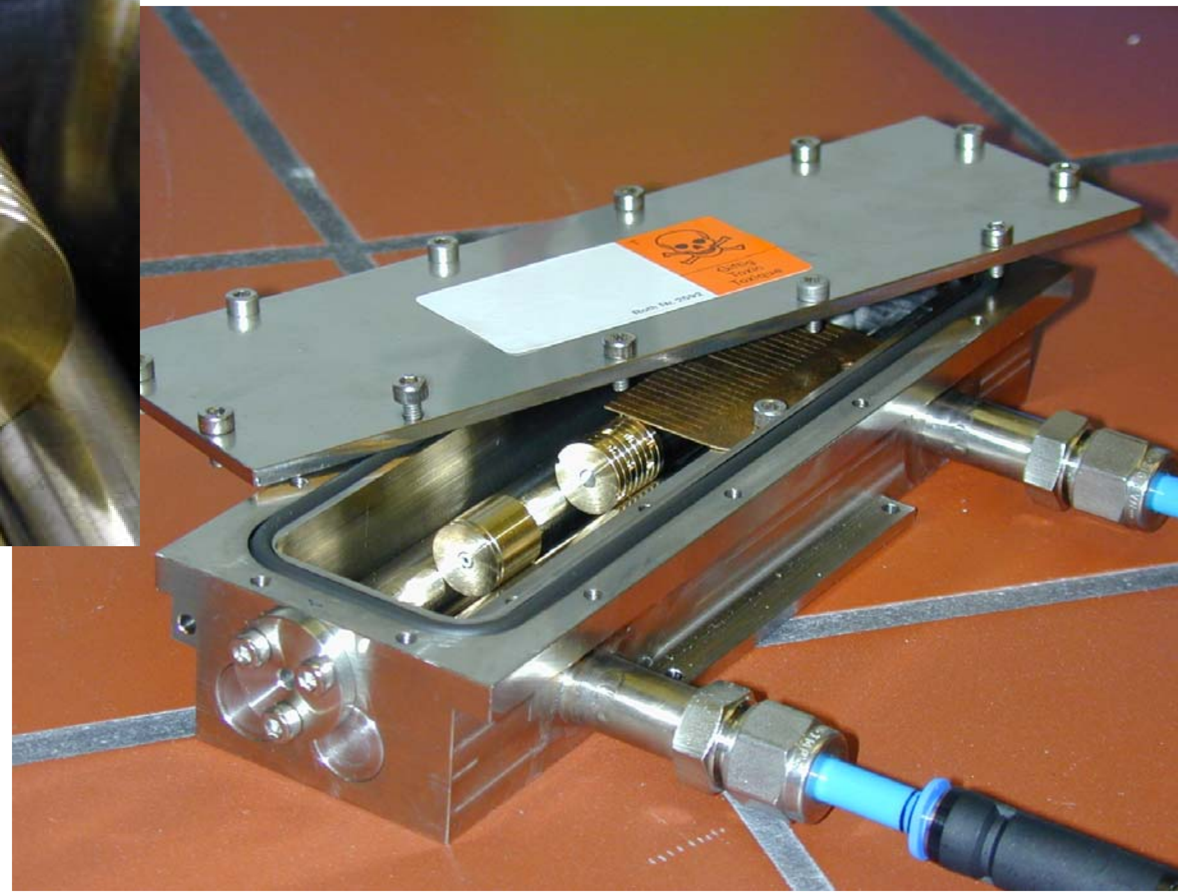
parabolic profile: No spherical aberration

→ imaging optic

C. Schroer (Tech Univ Dresden)

Parabolic Refractive X-Ray Lenses



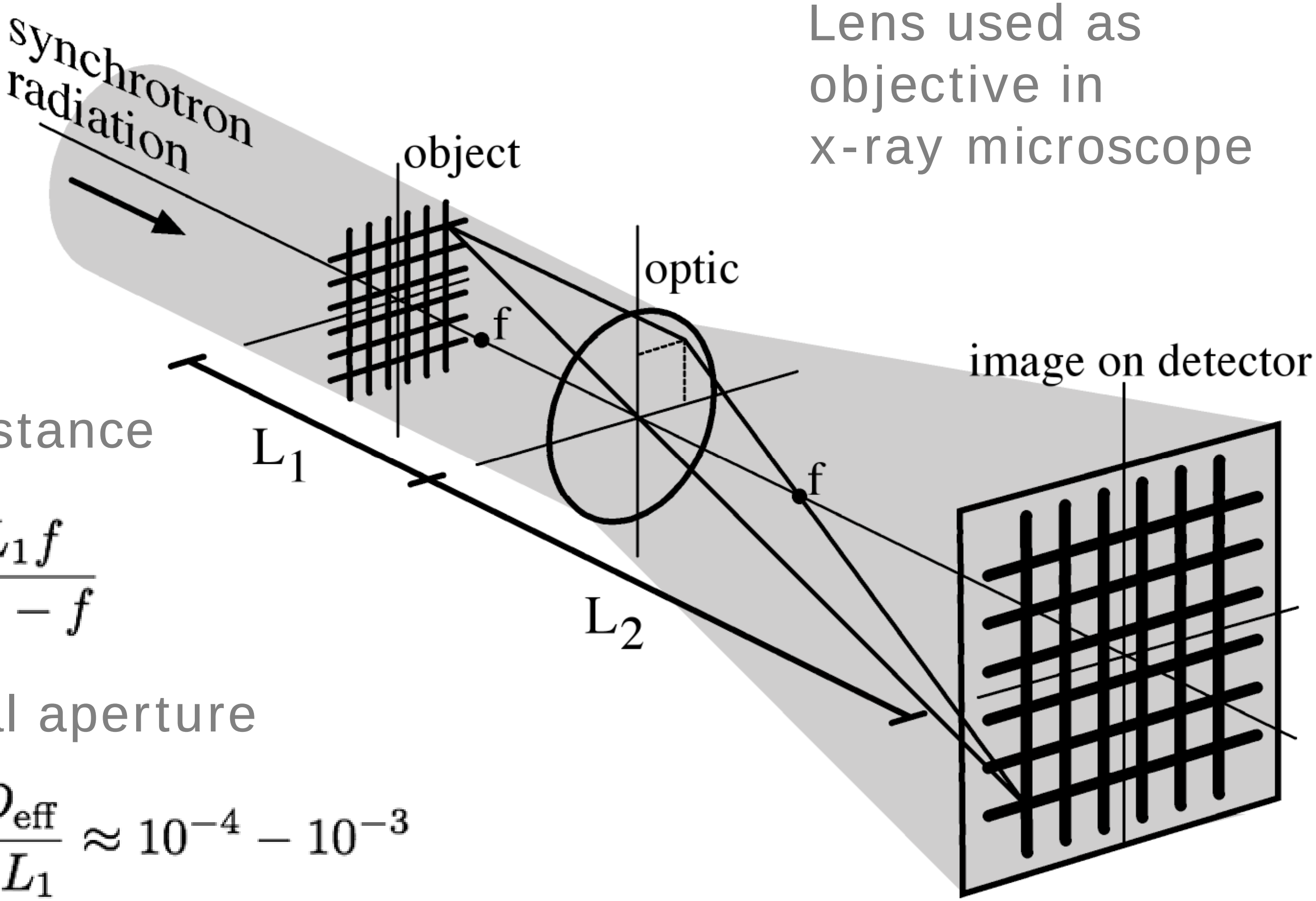


Aachen University

APL **74**, 3924 (1999)

C. Schroer (Tech Univ Dresden)

Imaging with Magnification



Lens used as objective in x-ray microscope

image distance

$$L_2 = \frac{L_1 f}{L_1 - f}$$

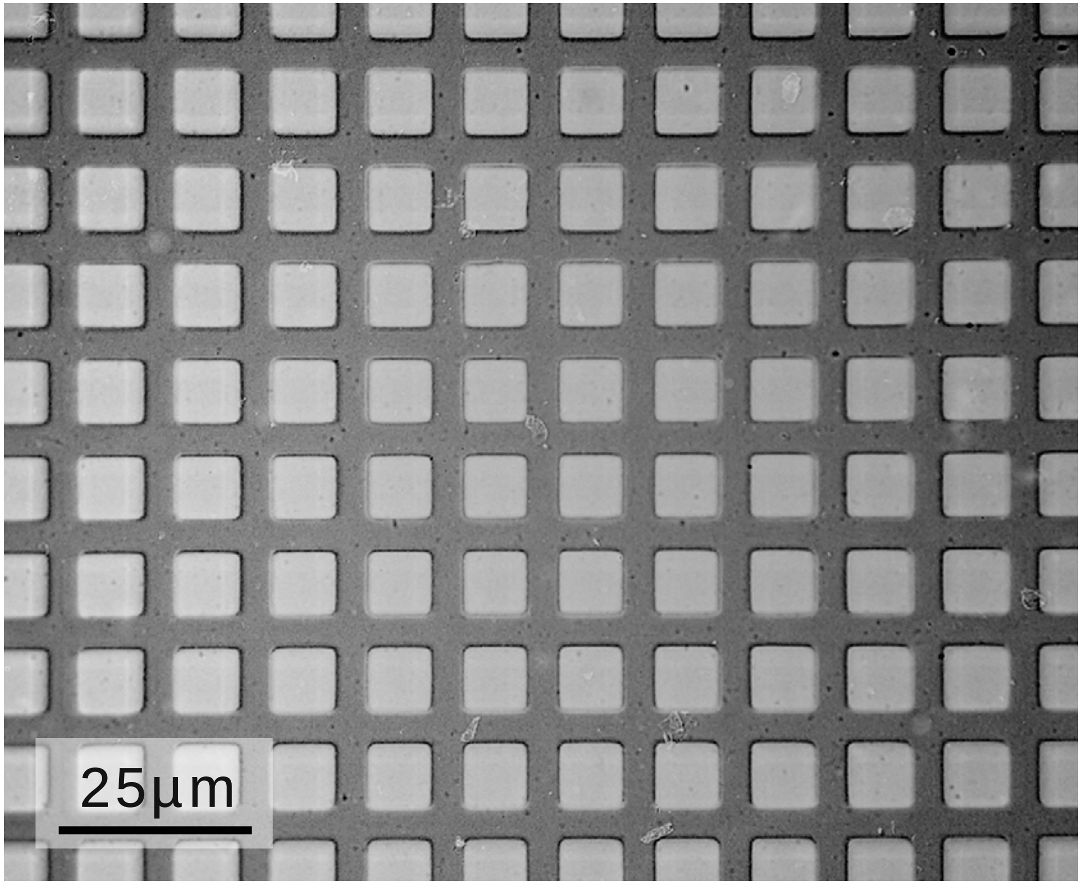
numerical aperture

$$NA = \frac{D_{\text{eff}}}{2L_1} \approx 10^{-4} - 10^{-3}$$

C. Schroer (Tech Univ Dresden)

Undistorted (Magnified) Image

Parabolic profile of lenses is crucial to good image quality

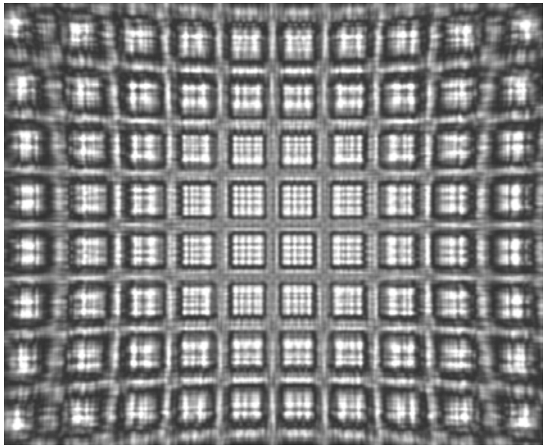


Ni-mesh (2000mesh)

parameters:

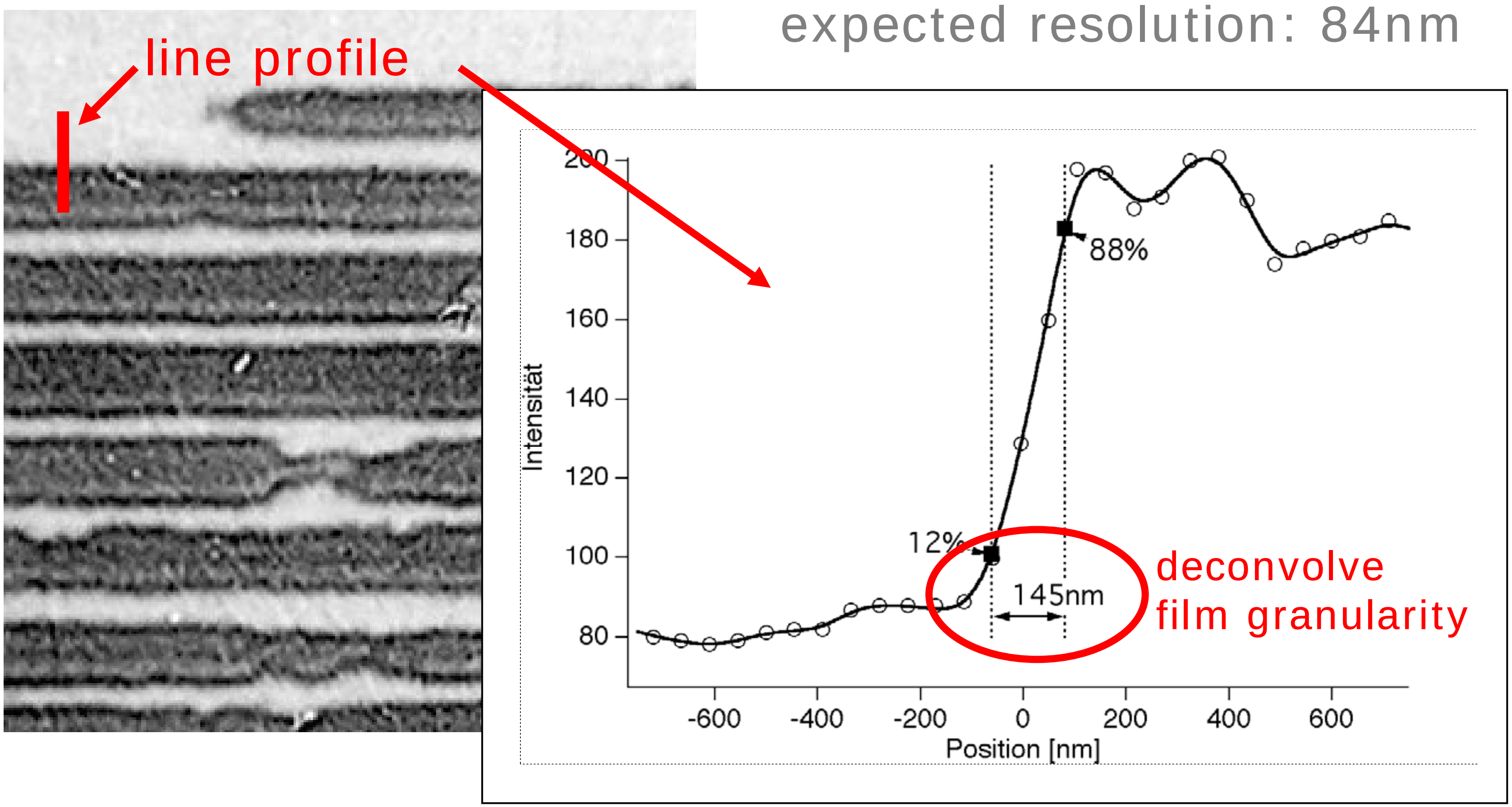
- E = 12keV
- N = 91 (Be)
- f = 495mm,
- m = 10x

simulation:
spherical lens



C. Schroer (Tech Univ Dresden)

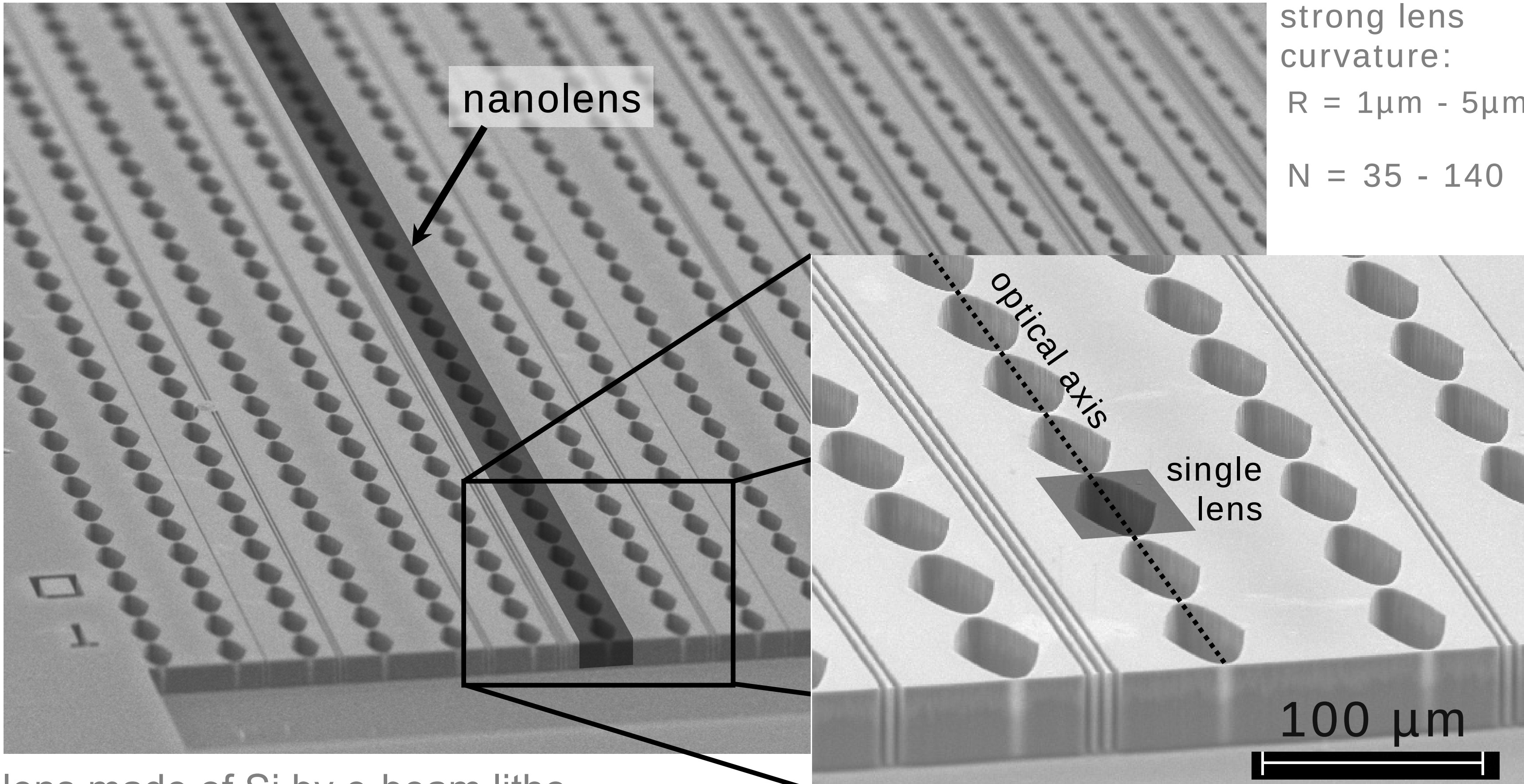
Full-Field Imaging: Resolution



→ resolution of Optic: 105nm ± 30nm

C. Schroer (Tech Univ Dresden)

1-Dimensional Nanofocusing Lenses (NFLs)



strong lens curvature:

R = 1µm - 5µm

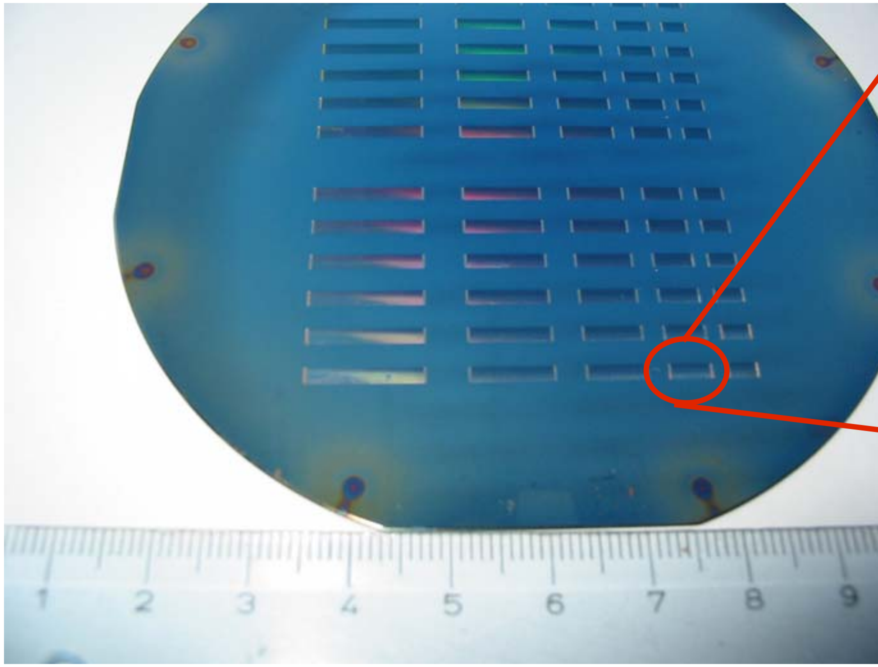
N = 35 - 140

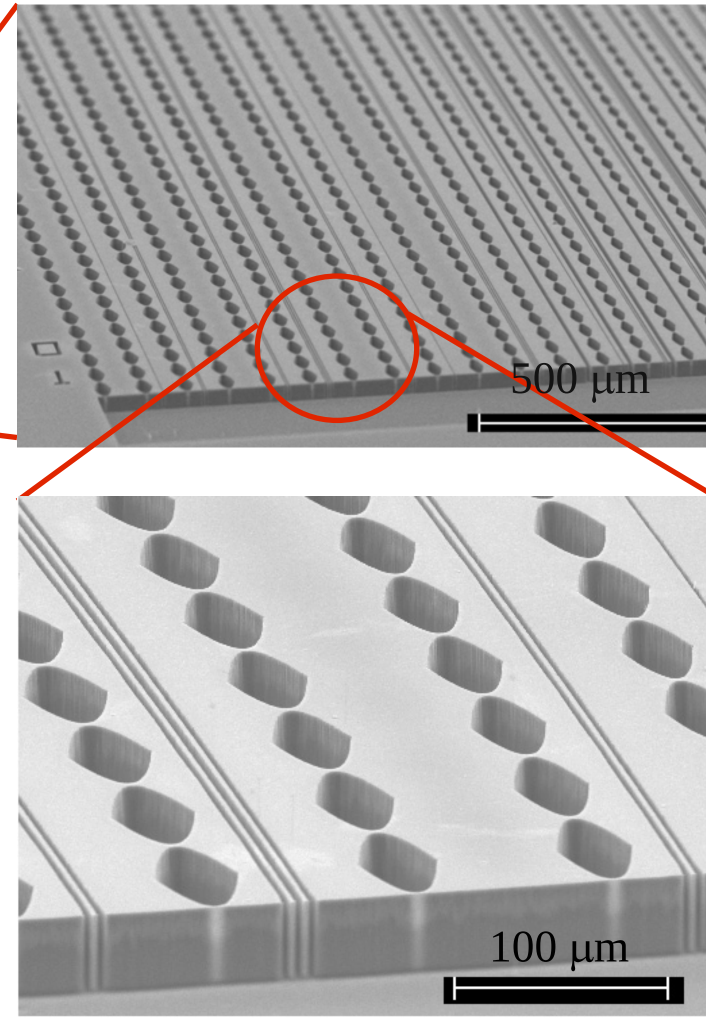
lens made of Si by e-beam lithography and deep reactive ion etching!

APL **82**, 1485 (2003)

C. Schroer (Tech Univ Dresden)

Fabrication of Si Nanofocusing Lenses



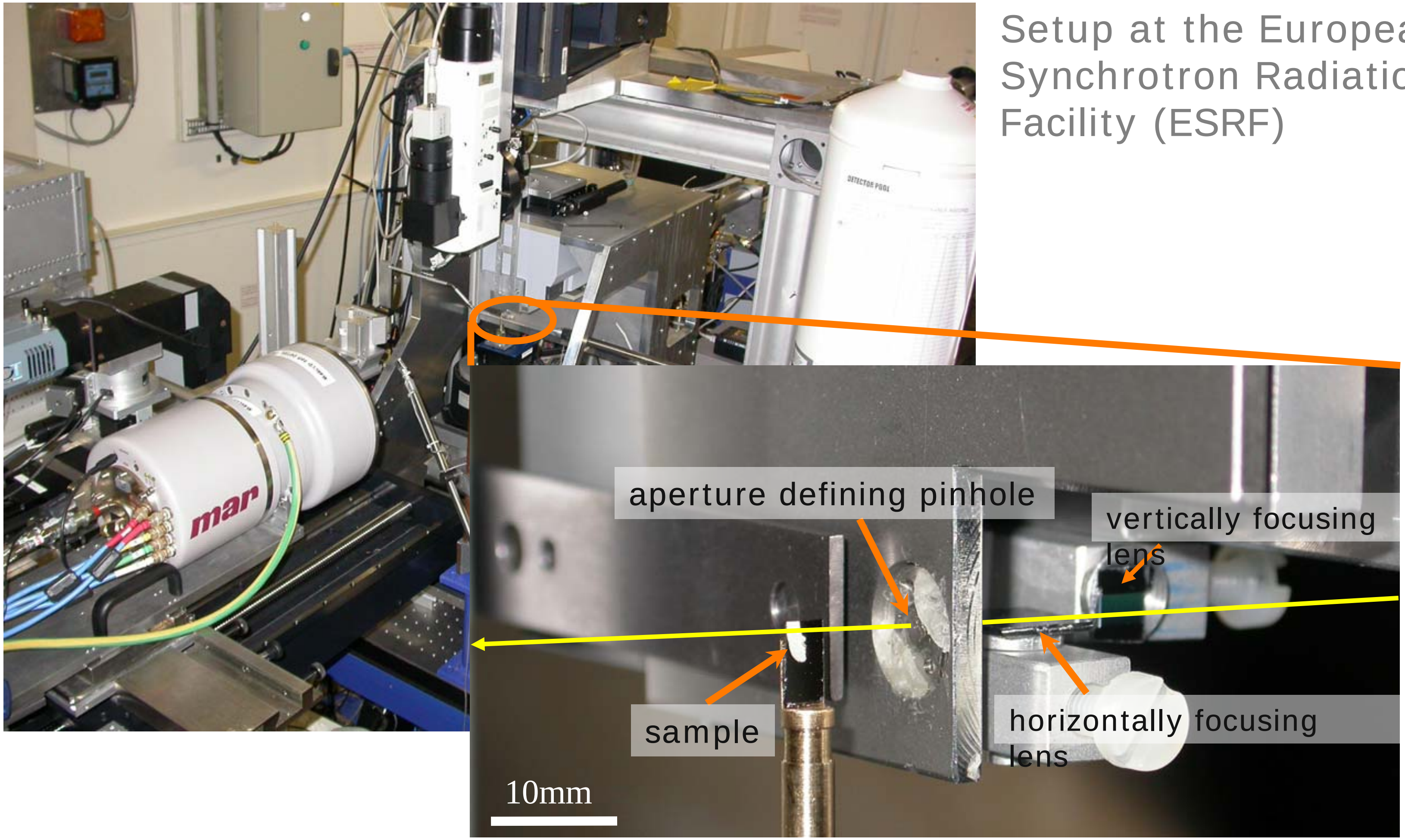


Over 1200 lens arrays
Over 100000 structures

→ high accuracy, reproducibility

C. Schroer (Tech Univ Dresden)

Crossed Nanofocusing Lenses



Setup at the European Synchrotron Radiation Facility (ESRF)

C. Schroer (Tech Univ Dresden)

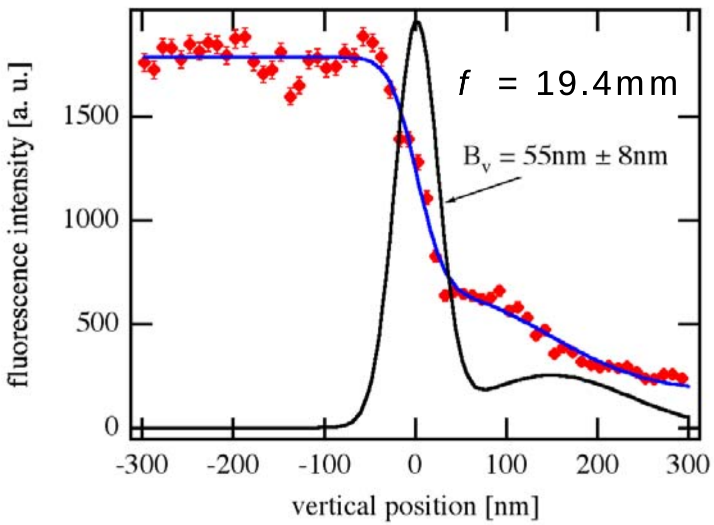
Focusing with NFLs

Si lens: E = 21keV, L_1 = 47m

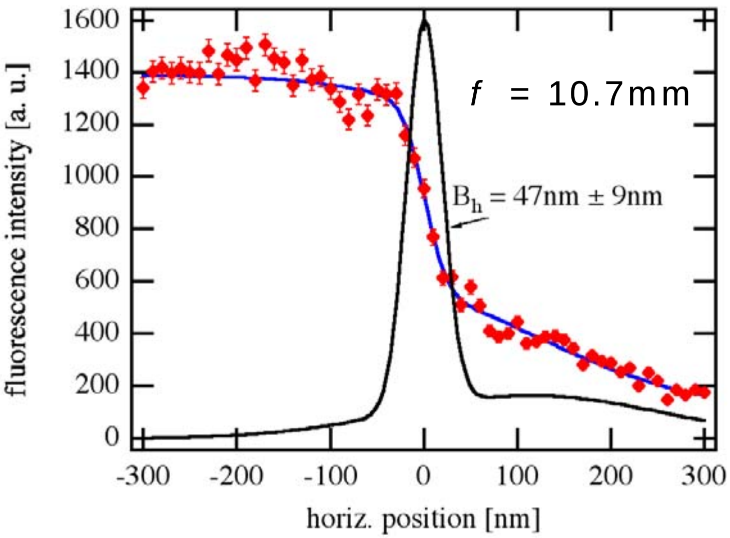
source:
ID13 low-β invac. undulator

source size: 150 x 60μm^2

vertical focus: 55nm



horizontal focus: 47nm



demagnification:
~ 2400 x 4400

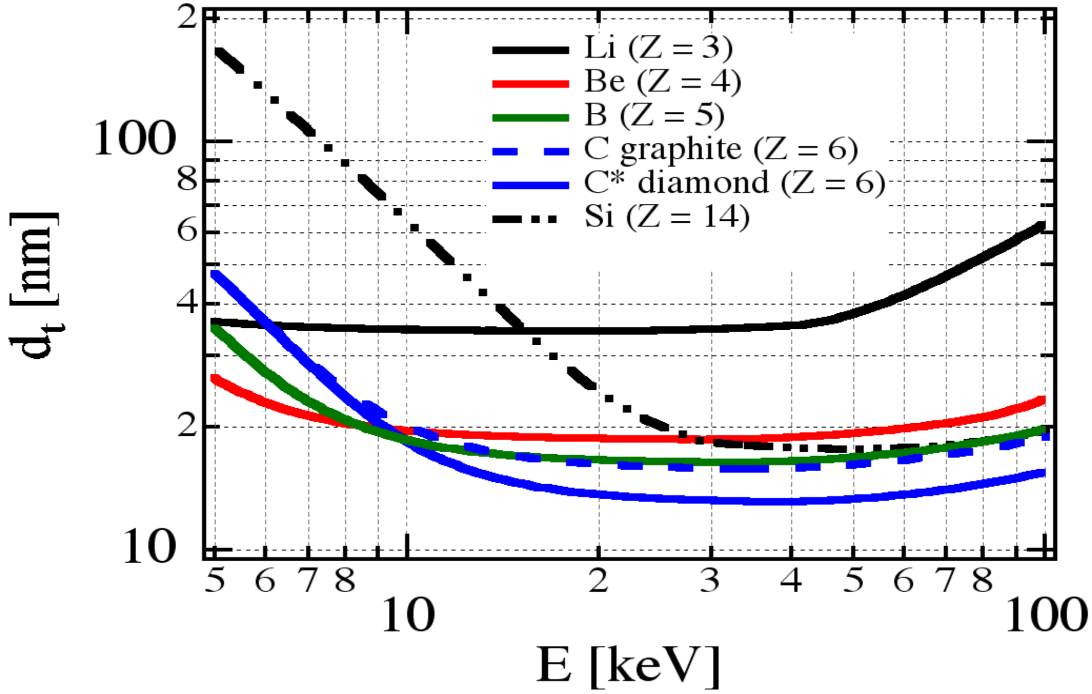
flux: 1.7 $\cdot 10^8$ph/s

APL **87**, 124103 (2005)

C. Schroer (Tech Univ Dresden)

Effective Aperture and Diffraction Limit

Diffraction limit:



N = 100
$l \geq 0.084$
R = 0.5 - 50µm

bounded by

$$0.75 \frac{\lambda}{2\sqrt{2\delta}} \propto \text{const.}$$

Best materials: high density and low Z

C. Schroer (Tech Univ Dresden)

Summary: best resolution achieved currently

- K-B mirrors : 25 x 30 nm

  H. Mimura *et al*., APL **90**, 051903 (2007);

  S. Matsuyama *et al*., RSI **77**, 103102(2006).

- FZP: 29 nm

  Y-T. Chen *et al*., Nanotech. **19**, 395302 (2008).

- MLL: 17 nm line focus

  H.C. Kang *et al*., APL **92**, 221114 (2008).

- CRL: 47 x 55 nm

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

- Waveguides: 25 X 47 nm

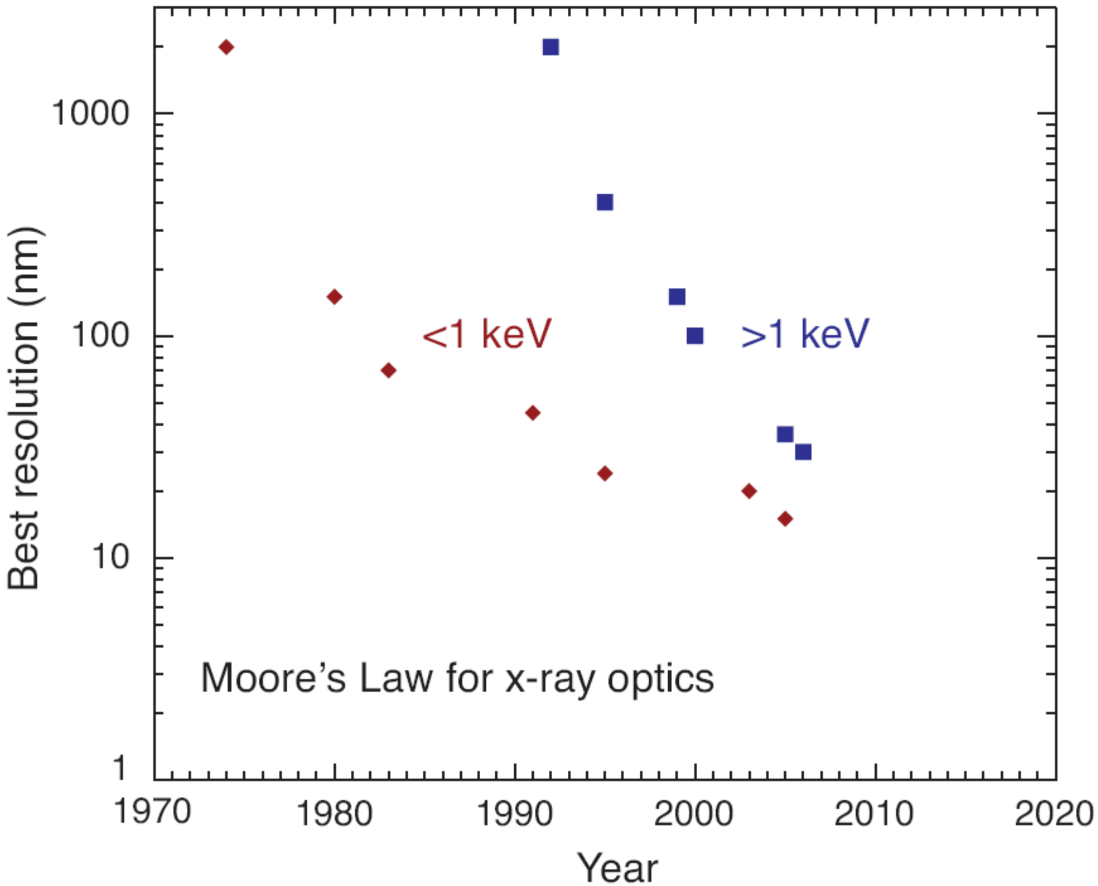
  A. Jarre *et al*., PRL **94**, 074801 (2005).

Summary: other considerations

	K-B mirror	FZP/MLL	Refractive Lens
Resolution	25 x 30 nm	29/17 nm	47 x 55 nm
Flux density gain	> 500,000	> 500,000	10,000
Chromatic aberration	Achromatic	$1/\lambda$	$1/\lambda^2$
Coherence preservation	Fair	Good	Acceptable
Easy to use	Require effort	Good	Fair

Future Prospects

Resolution had improved dramatically



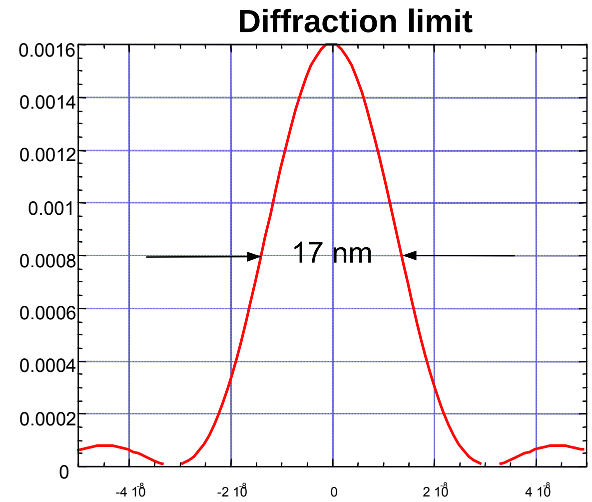
Year	nm	keV	Method	Notes and citation
1974	2000	0.28	ZP (holographic)	Full-field [Niemann et al., 1974]
1980	150	0.28	ZP (holographic)	Full-field [Schmahl et al., 1980]
1983	70	0.28	ZP (holographic)	Full-field [Niemann et al., 1983]
1984	300	0.32	ZP (e-beam)	Scanning [Rarback et al., 1984]
1988	75	0.32	ZP (e-beam)	Scanning [Rarback et al., 1988]
1991	45	0.32	ZP (e-beam)	Scanning [Jacobsen et al., 1991]
1992	2000	8.2	ZP (e-beam)	Scanning [Yun et al., 1992]
1995	24	0.54	ZP (e-beam)	Full-field [Schneider et al., 1995]
1995	400	8	ZP (e-beam)	Scanning [Lai et al., 1995]
1997	20	0.32	ZP (e-beam)	Scanning [Spector et al., 1997]
1998	3500	18.8	CRL	Scanning [Lengeler et al., 1998]
1999	2400	13.3	BFL	Scanning [David and Souvorov, 1999]
1999	150	4.0	ZP (e-beam)	Full-field [Kaulich et al., 1999]
2000	100	2.5	ZP (e-beam)	Scanning [David et al., 2000]
2001	200	19	KB mirrors	Scanning [Hignette et al., 2001]
2001	480	9.7	CRL	Scanning [Schroer et al., 2001]
2003	19.5	0.6	ZP	Full-field [Chao et al., 2003]
2005	90	20.5	KB mirrors	Scanning [Hignette et al., 2005]
2005	36	15	KB mirrors	Scanning [Yumoto et al., 2005]
2005	15	0.80	ZP (e-beam)	Full-field [Chao et al., 2005]
2006	30	19.5	MLL	Scanning [Kang et al., 2006]
2006	19	19.5?	MLL	Scanning (Kang *et al.*; unpublished)
2006	24	15?	KB mirrors	Scanning (Yumoto *et al.*; unpublished)
2005	60	5.4	ZP (e-beam)	Full-field (Xradia, Inc.; published?)

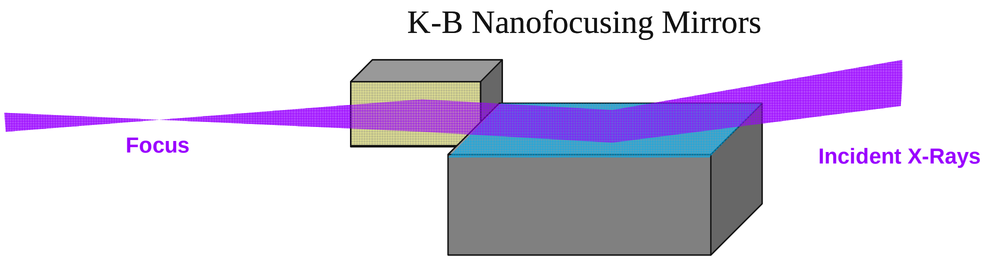
C. Jacobsen (Stony Brook)

Where is the limit? 1 nm? 1 Å?

Reflective Optics: Focal size ultimately limited by θ_c

- δ(nm) ~ $100\lambda_C$(Å)/$\Delta\theta$(mrad)
- $\Delta\theta \sim 0.85\theta_c$ standard KB mirror
- θ_c ~ proportional to λ
  δ ~ 17 nm- Pt 50% reflectivity
  δ ~ 14 nm- Pt 10% reflectivity



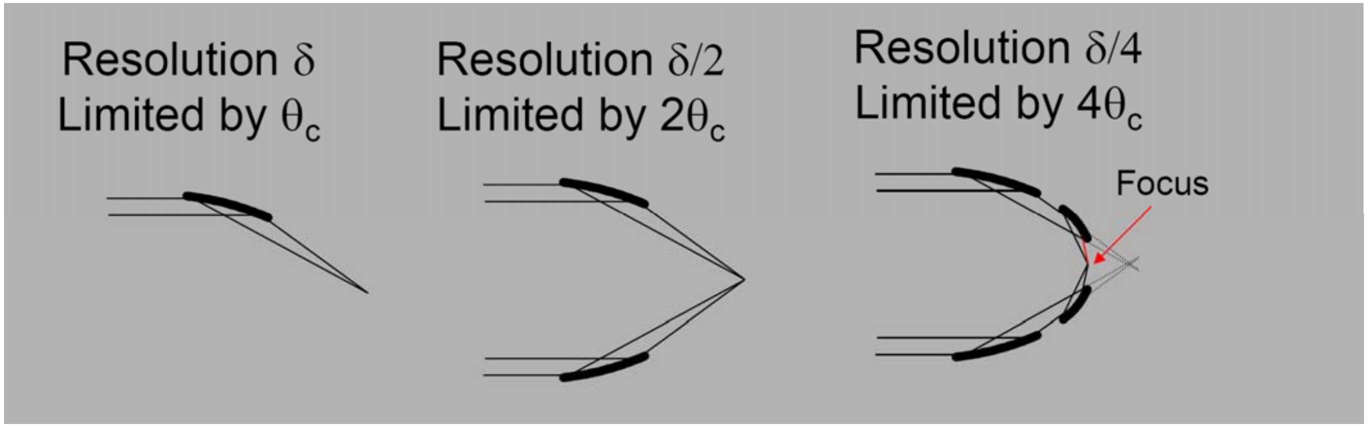


G. Ice (ORNL)

Reflective optics: radical approaches needed for sub 10 nm

- **Multilayers → 4-5 nm**
  - **ESRF/Osaka**
  - **Limited bandpass - ideal for undulator harmonic**

- **Coaxial/multiple reflections → 3-4 nm**

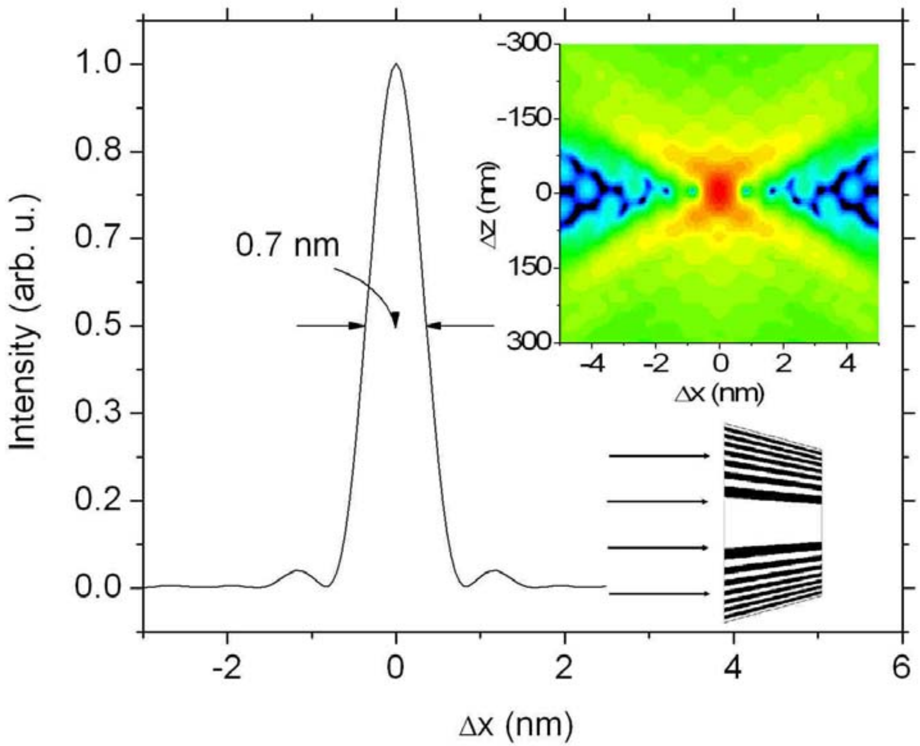


- **Combination of both →→ 1 nm?**

G. Ice (ORNL)

MLL: Presently Feasible Outermost Zone Width

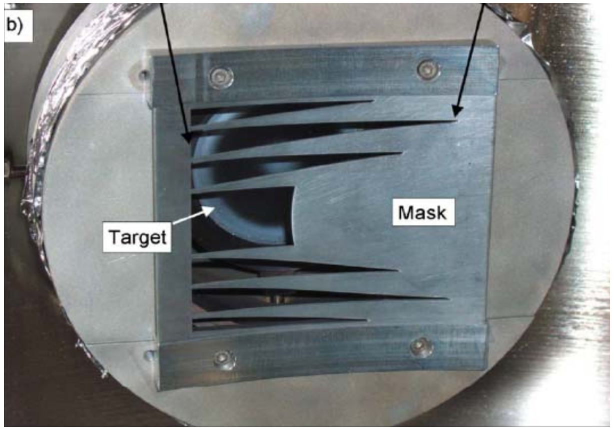
(0.75 nm layer width has been demonstrated: Y. Chu et al., RSI 73, 1485 (2002))



Calculated for:

- Wedged zones
- Outermost zone width: 0.75 nm;
- Energy: 19.5 keV
- Efficiency: 50%
- Radius: 40 microns

Lateral gradient mask on sputtering target: wedge MLL

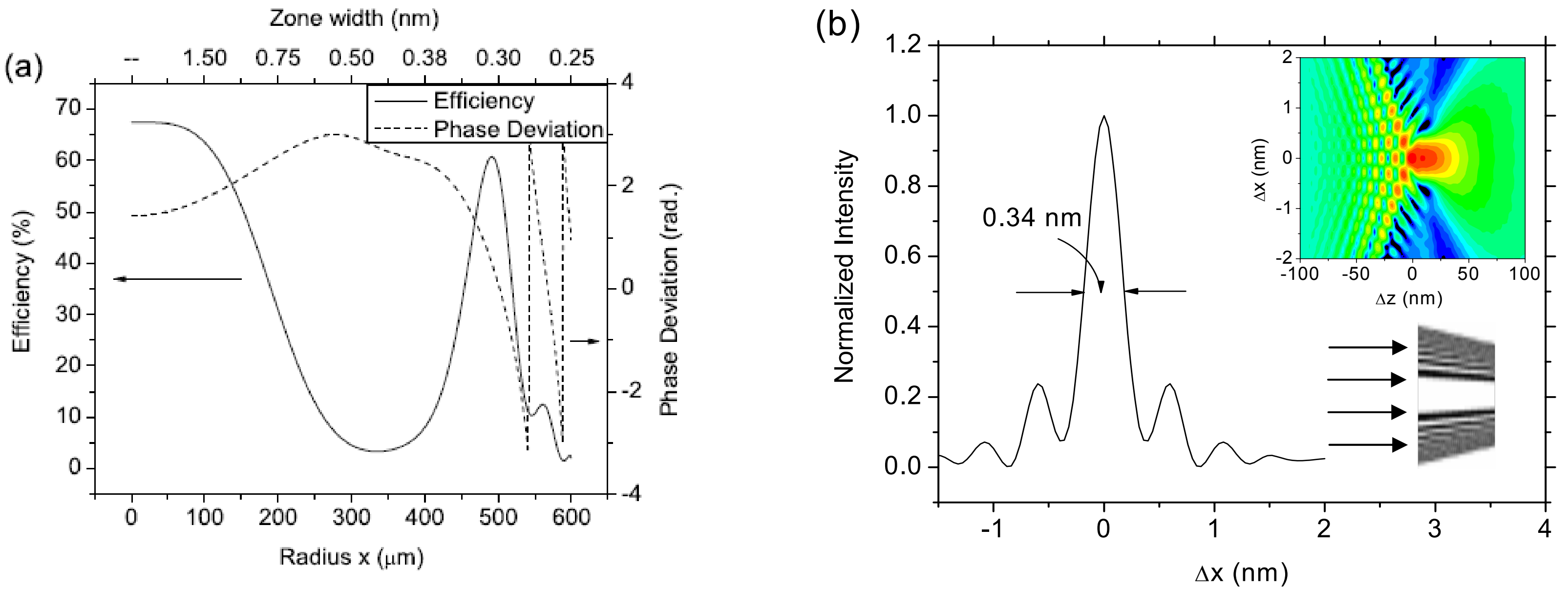


H.C. Kang , H. Yan, et al., submitted

MLL: when Δr ~ single atomic layer

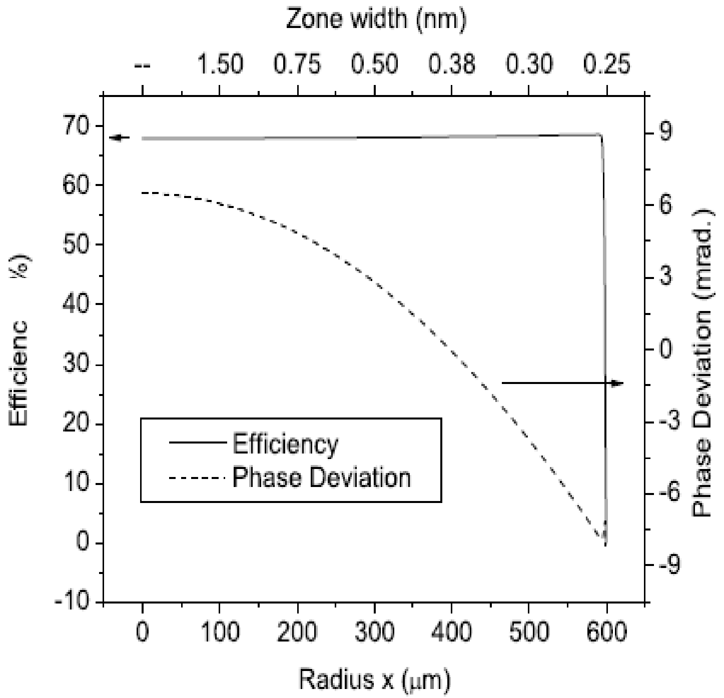
Each zone is tilted progressively to satisfy the local Bragg condition, resulting in a wedged shape.

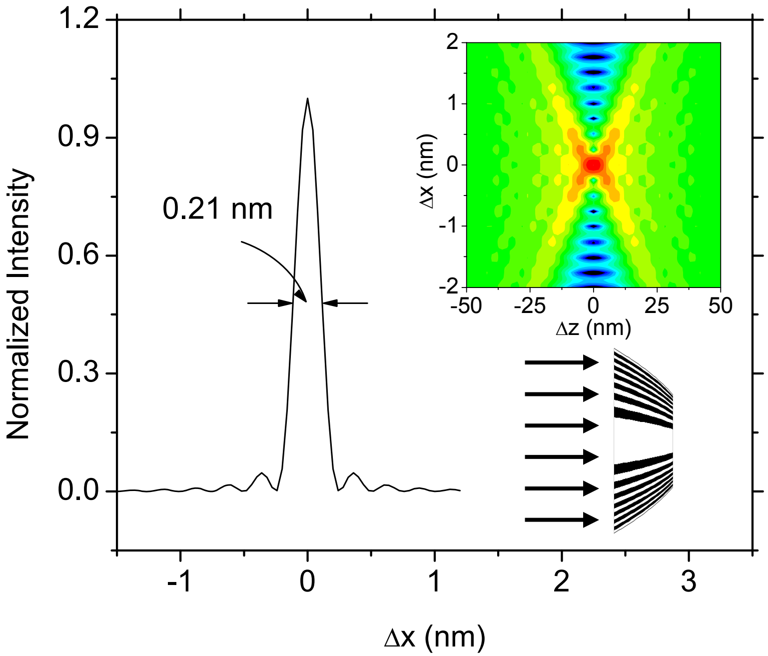
Outermost zone width : 0.25 nm



H. Yan *et al*., PRB **76**, 115438 (2007).

Ultimately parabolically curved interfaces are needed





H. Yan *et al*., PRB **76**, 115438 (2007).

Refractive Lens: Adiabatically Focusing Lens (AFL)

Current limitation:

geometry of lens limits refractive power per unit length for given aperture:

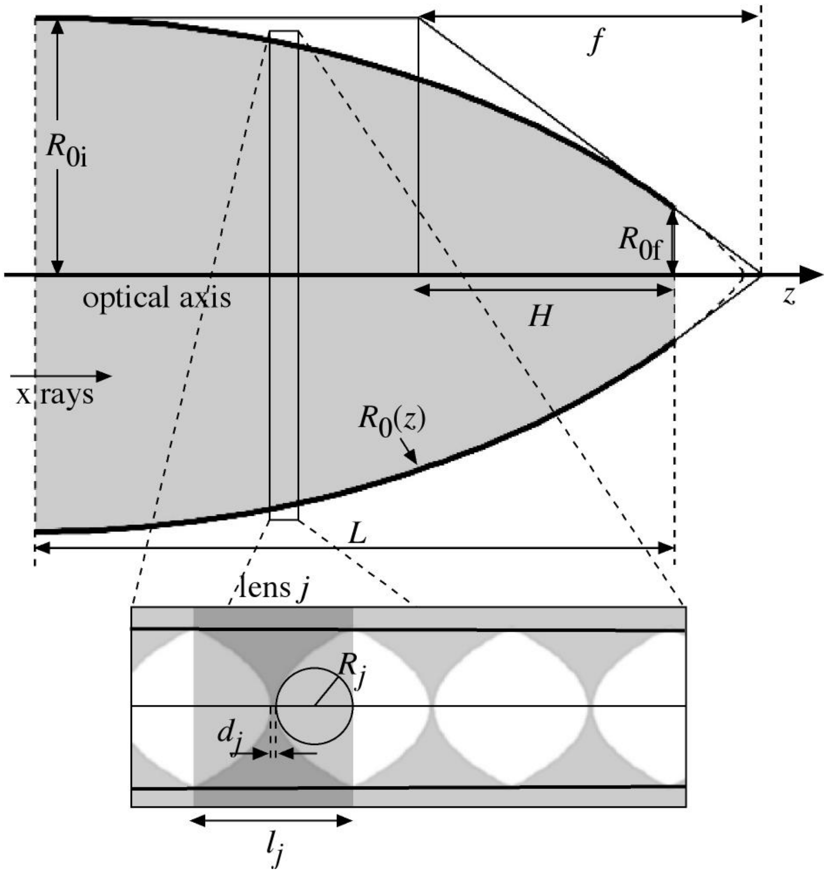
$$\frac{1}{l f_s} = \frac{2\delta}{lR} \approx \frac{2\delta}{R_0^2}$$

Solution:

adjust R_0 to fit the converging beam as it is focused

PRL **94**, 054802 (2005)

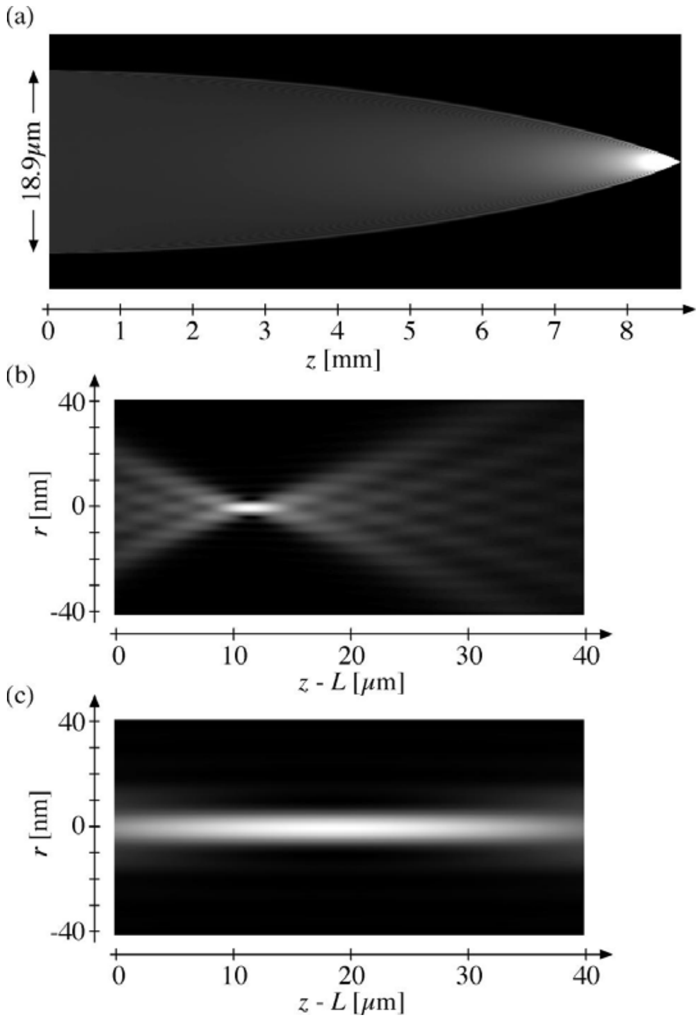
adiabatically focusing lens (AFL)



C. Schroer (Tech Univ Dresden)

Example AFL

contracting wave field inside lens



Diamond lens:

low atomic number *Z* and high density ρ

N = 1166 individual lenses
entrance aperture: 18.9µm
exit aperture: 100nm
f = 2.3mm

diffraction limit: 4.7nm

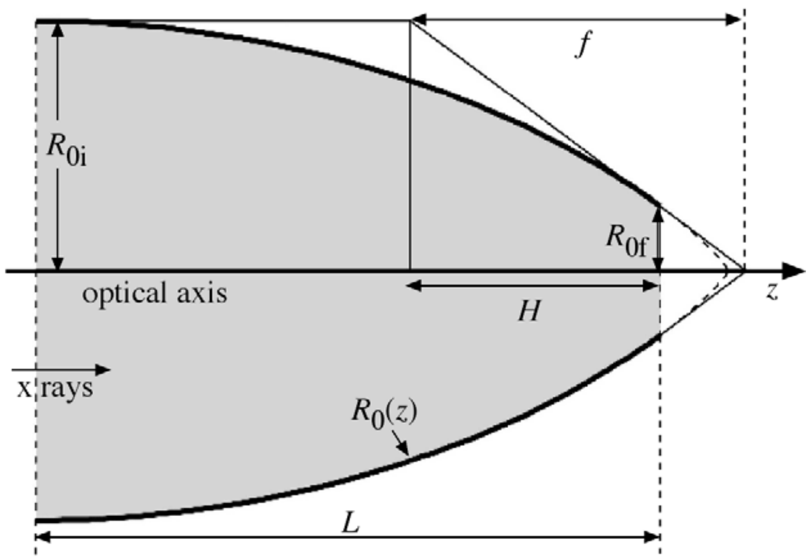
compare to NFL:
same aperture

diffraction limit: 14.2nm

C. Schroer (Tech Univ Dresden)

AFLs Made of Silicon

entrance aperture: $2R_{0i}$ = 20µm
exit aperture: $2R_{0f}$ = 1µm
energy: 10 - 20keV in 500eV steps



properties:

f = 2.7mm
d_t = 12.6nm

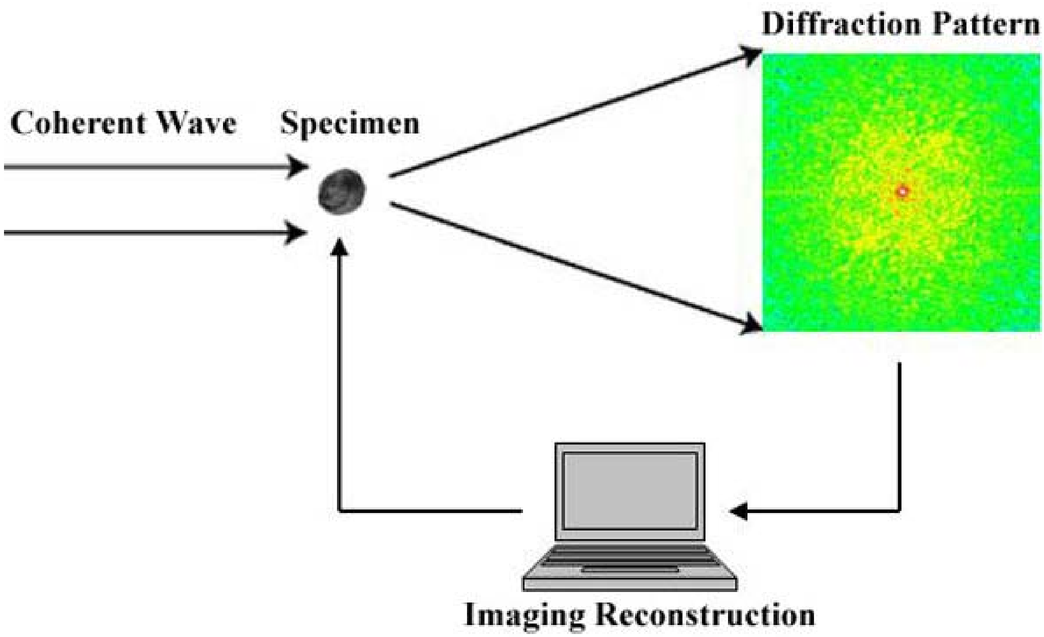
as horizontal lens in x-ray nanoprobe (e. g. ID13 ESRF):

L_1 = 47m, source size: 150µm

horizontal focus: 15.3nm
(17400 x reduction)

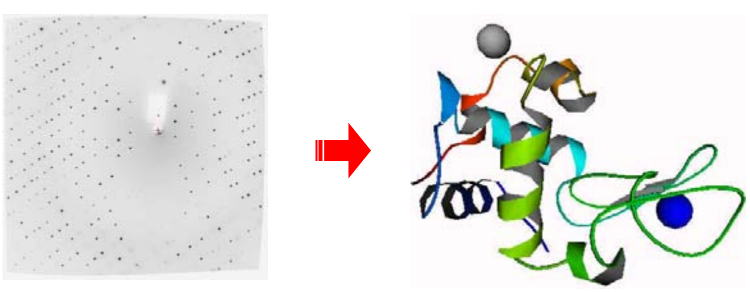
C. Schroer (Tech Univ Dresden)

(Lensless) Coherent Diffraction Imaging

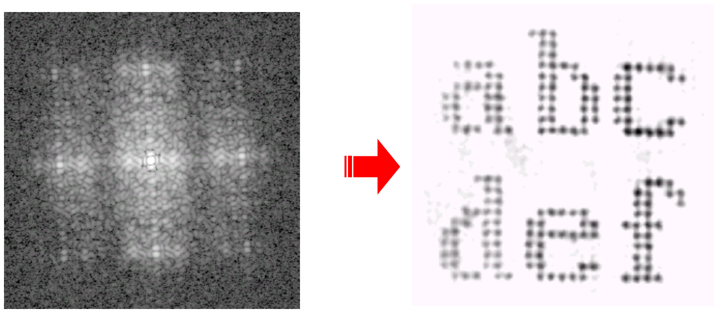


- ➔ Coherent diffraction imaging is much like crystallography but applied to noncrystalline materials
- ➔ Lateral resolution can in principle approach λ, not limited by N.A. of available optics. Long depth of focus.
- ➔ Requires a fully coherent x-ray beam

Analogous to crystallography



Miao et al. (1999)



Conclusions

- Microfocusing optics is an vibrant field with many parallel developments:
  - Reflective optics
  - Diffractive optics
  - Refractive optics
- Resolution had improved dramatically over the last two decades. 30-50 nm are currently available.
- Future spot size of a few nm is physically possible, but requires great engineering effort. There may be sufficient sensitivity and resolution to detect single atoms?
- However, microprobes of all length scale are required for most scientific studies. It is likely that 10 nm – 10 μm will remain the primary workhorse.