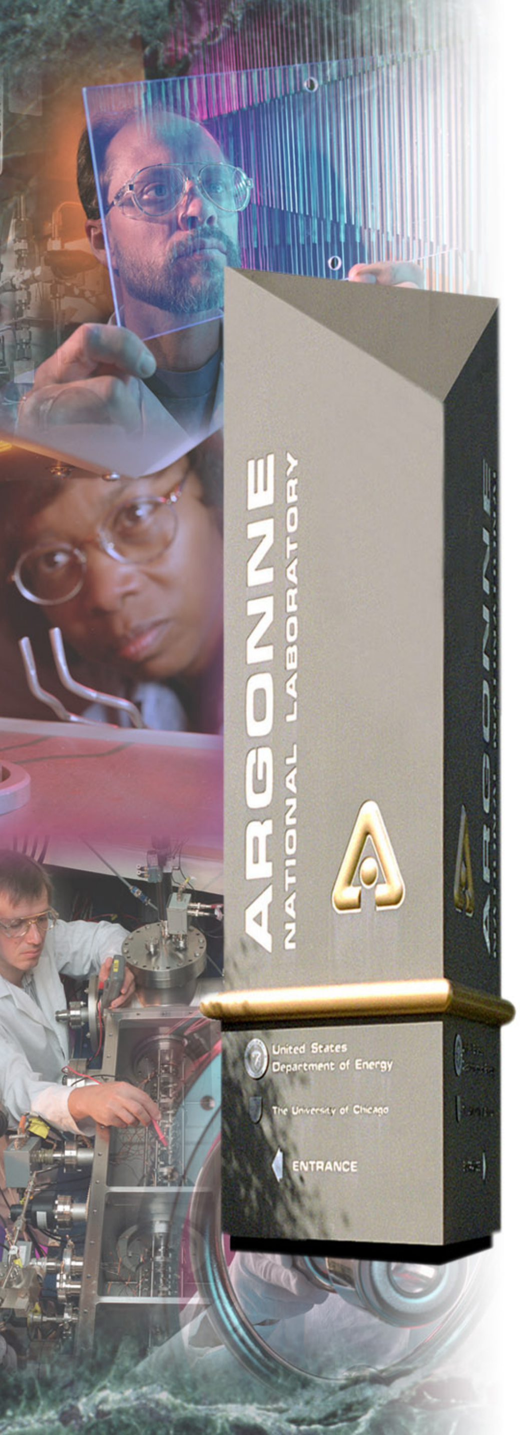

Multilayer Laue Lenses:

a Path towards Nanofocusing of Hard X-rays

National Synchrotron Light Source

May 31, 2006

Jörg Maser

X-ray Science Division

Center for Nanoscale Materials

Argonne National Laboratory

THE UNIVERSITY OF CHICAGO

Office of Science
U.S. DEPARTMENT OF ENERGY

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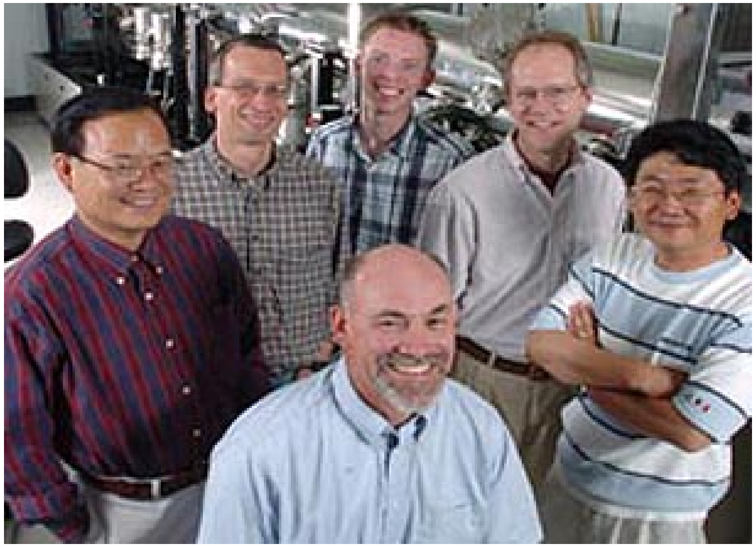
Collaborators

- Hyon Chol Kang: X-ray characterization of MLL; Polishing of MLL
- Brian Stephenson: X-ray characterization of MLL
- Al Macrander, Chian Liu, Ray Conley: Deposition of MLL
- Stefan Vogt, Fourier Optics
- Hanfei Yan



Outline

I) Introduction: Why do we care about focusing of X-rays?

II) Properties of X-ray optics - Overview

III) Nanometer Focusing of X-rays - Volume Diffractive Optics

IV) Technical Approach to Nanofocusing - Multilayer Laue Lenses

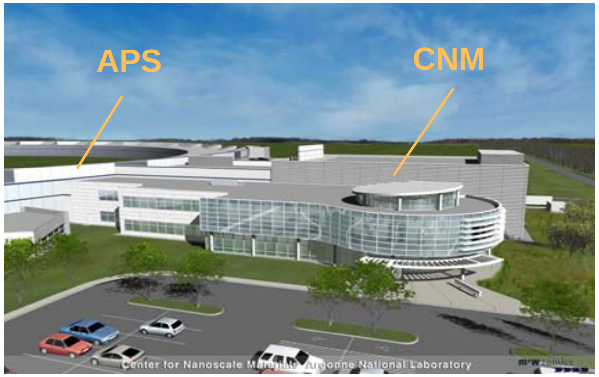
V) Summary/Outlook: where does the MLL approach lead? How does the ultimate x-ray optic look?

VI) Acknowledgments

Thrust: Towards Ultimate Resolution Limits for X-rays

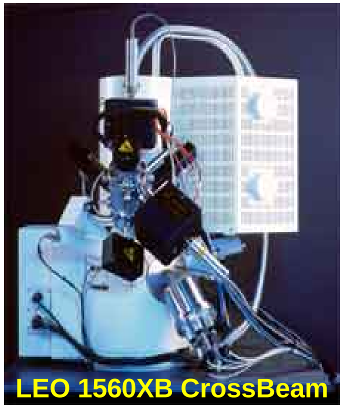
I) Why do we care about X-ray Focusing?

Argonne's Center for Nanoscale Materials



- Mission:
  - "Explore and develop new approaches to fabrication, characterization and understanding of nanoscale confined materials with new properties"

- Major fabrication/characterization tools:
  - E-beam lithography (25 kV, 100 kV systems)
  - FIB/SEM
  - Near-Field Scanning Optical Microscope
  - Hard X-ray Nanoprobe Beamline (30 nm initial resolution, instrument design for < 10 nm)


LEO 1560XB CrossBeam

Nanoprobe Beamline Layout:

Double mirror system:

M1a: fully illuminated, horizontally bent

M1b: flat

PD = 0.5 - 4 W/mm^2

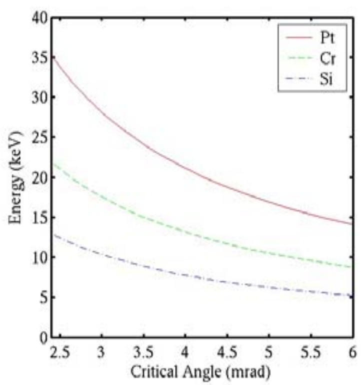
P_{tot} = 70 - 730 W

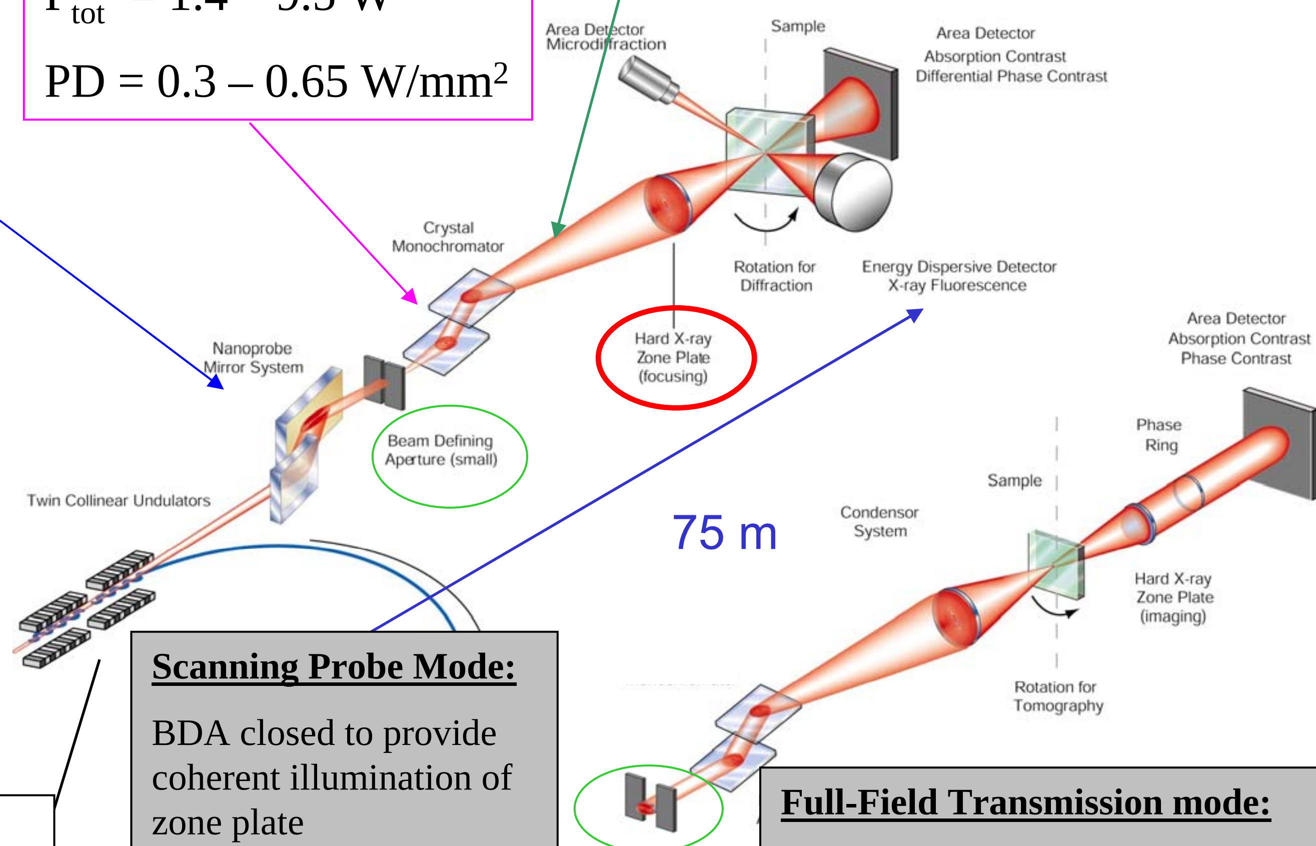
Crystal monochromator

P_{tot} = 1.4 – 9.5 W

PD = 0.3 – 0.65 W/mm^2

Polarizer, beam chopper





Twin undulators:

PD = 905 W/mm^2 @ 25.5 m

P_{tot} = 20.7 W @ I = 180 mA

Scanning Probe Mode:

BDA closed to provide coherent illumination of zone plate

Full-Field Transmission mode:

BDA open to provide coherent illumination of zone plate

II) What we would like from High-Resolution X-ray Optics

- Requirements:
  - Highest spatial resolution
    - *Ideally: wavelength limited (1 Å) NA $\rightarrow$ 1.*
  - High focusing/imaging efficiency
    - *Ideally 100%*
  - Large acceptance (focusing: accept full coherent fraction of beam)
  - Full-field imaging capability
    - *Example: 500 x 500 pixels*
- Desired:
  - Energy tunability
  - Broad bandpass
  - (Easy alignment)

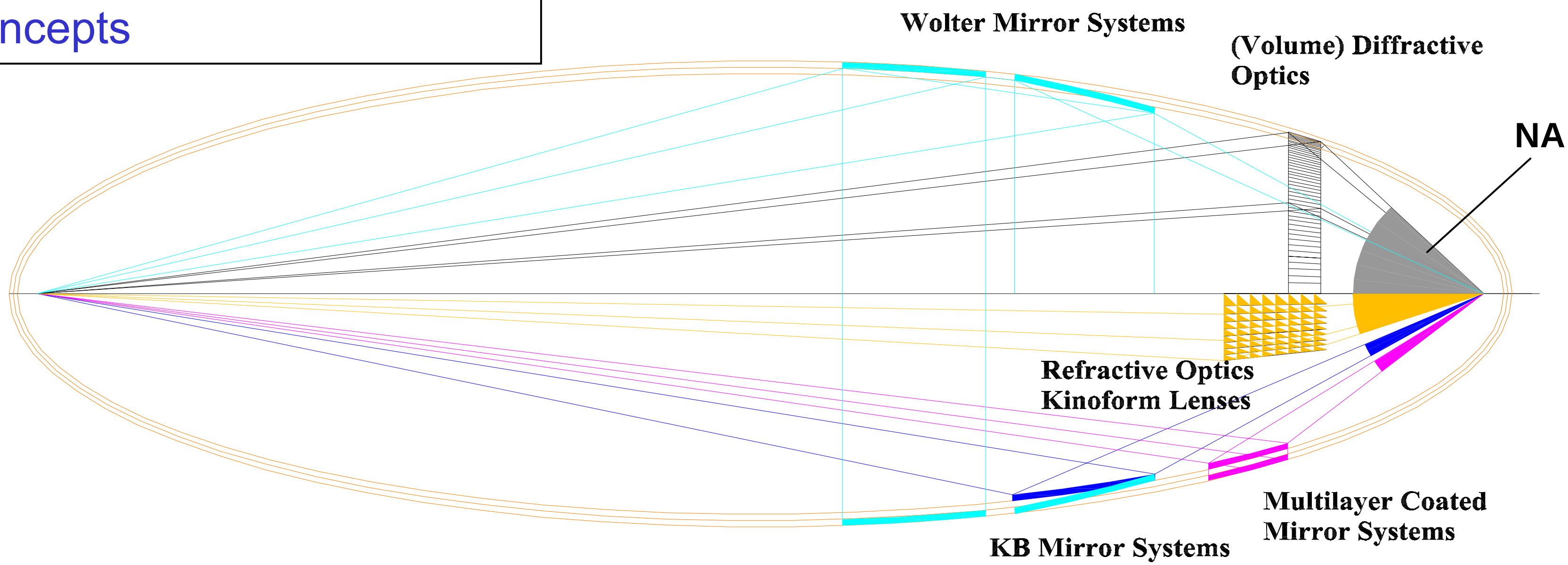
Far-Field Focusing of X-rays – Conceptual Approaches

Interaction of x-rays with matter:

$$n = 1 - \delta - i\beta, \quad 0 < \delta, \beta \ll 1 \quad (\delta \sim 10^{-5}, \beta \sim 10^{-6}, \text{W, 20 keV})$$

- $\delta > 0$ $\rightarrow$ Total external reflection for $\theta < \theta_c$
- $\beta > 0$: Absorption
- $\delta \ll 1$ Weak interaction $\rightarrow$ Good focusing efficiency challenging for high numerical aperture

Far-field Focusing/Imaging Concepts



Properties of Far-Field X-ray Optics

X-ray optic	Diffractive Optics	Reflective Optics	Refractive Optics
Numerical aperture	• High NA possible Limits: Volume diffraction? Fabrication	• Limited NA (θ_c) – KB: NA ≅ ½ (2·θ_c) – Wolter: NA ≅ 4θ_c – Multilayer: NA ~ m·θ_c	• Limited aperture: $\beta > 0 \rightarrow D_{eff} < D$
Resolution limit	< 1 nm?	– KB: ~ 16 nm/*m* – Wolter: ~ 3 nm/*m*	CRL: ~ 20 nm A-CRL: $\beta = 0$: ~ 2 nm → Fresnel lens: CFL?
Efficiency	20% - 30% (60%-80%)	70% - 90%	20% - 30%
Chromaticity	f ~ 1/λ	Non-chromatic (*m = 1*)	f ~ $1/\lambda^2$
Field of view	Y (δ > 10 nm) N (δ << 10 nm)	• Kirkpatrick/Baez: N • Wolter Y	Y
Other	• Monochromatic beam • On-axis geometry • Any x-ray energy	• White (pink) beam (non-ML) • Grazing inc. geometry. • Any x-ray energy • KB: working distance!	• Monochromatic beam • On-axis geometry • Limited energy range • Long lenses
Limitations	• (High aspect ratio/tilt) • Positioning/alignment	• Figure errors	• Small working distance at high resolution

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X-ray Focusing and Imaging – Current State of the Art

- State of the art in x-ray imaging and focusing (2D focus):
  - Refractive Optics: $\delta \sim 50$ nm (E = 21 keV) (*Schroer, APL, 2005*)
  - Reflective Optics: $\delta \sim 40$ nm (E ~ 15 keV) (*Mimura, JJAP 2005*)
  - Diffractive Optics: $\delta \sim 15$ nm, (E = 0.8 keV) (*Chao, Nature, 2005*)

- Spatial Resolution limit of optics: $\delta = c \cdot \lambda / NA$, c = 0.5 (1D) – 0.6 (2D)
  - NA = 1 $\rightarrow$ $\delta \approx \lambda$ (λ = 0.6 Å, E = 20 keV)

- What is the ultimate resolution limit for x-ray focusing?
  - Diffractive optics: ~ 1 nm (*Kang, 2006*); Å feasible?
  - Reflective Optics: ~ 16 nm (KB). 3 nm (Wolter) (non-ML)
  - Refractive Optics: ~ 2 nm (β = 0, *Schroer, 2005*)

III) Nanometer focusing using Diffractive Optics:

→ Volume Diffractive Optics

Section III: What is the physics of volume diffraction?

- Change of d-spacing
- Weak interaction: t large (t > DOF for high NA)
- Dynamic Effects

- Energy tunability
- Full-field imaging

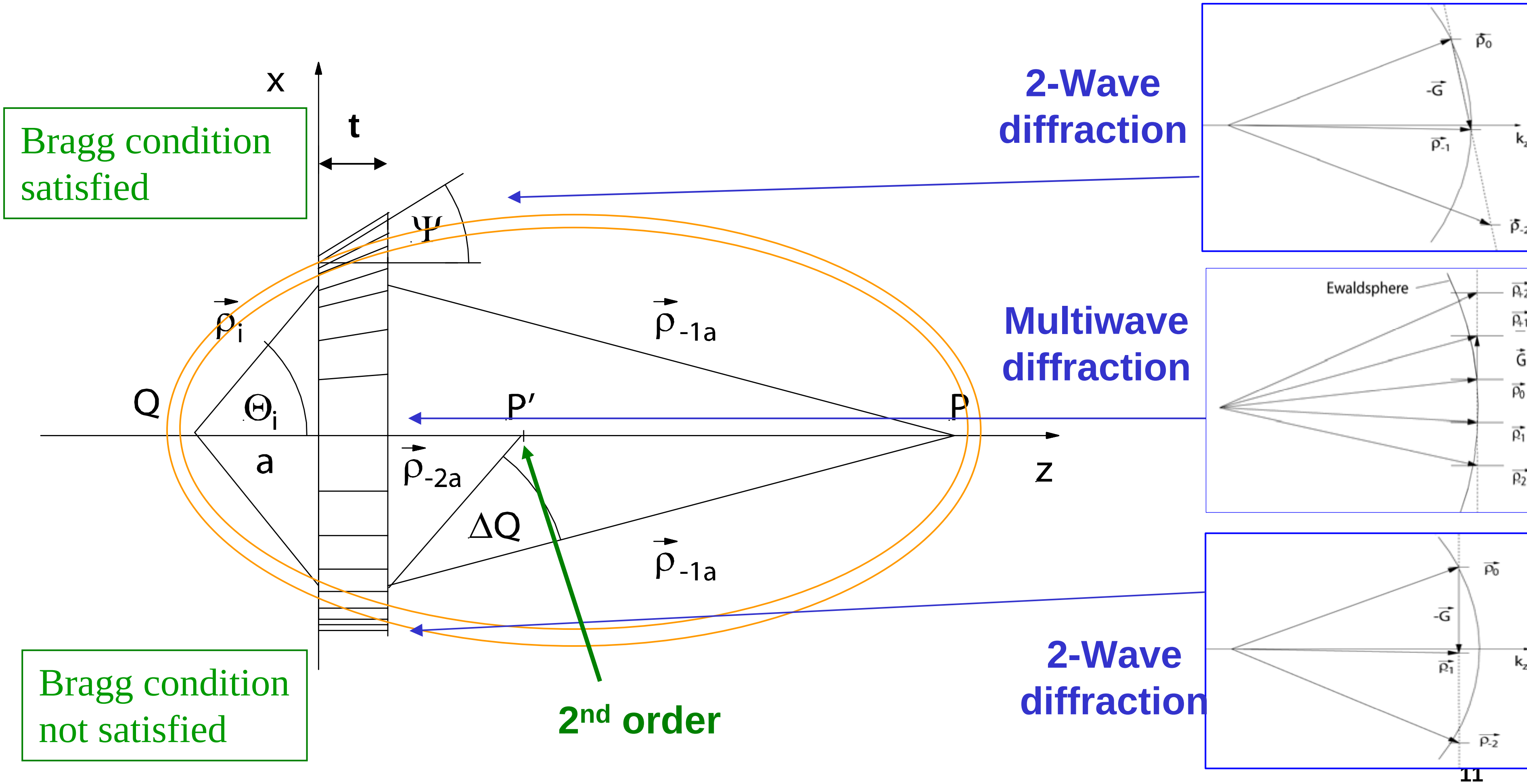
Section IV: How to fabricate volume diffractive optics with large NA?

→ Multilayer Laue Lens

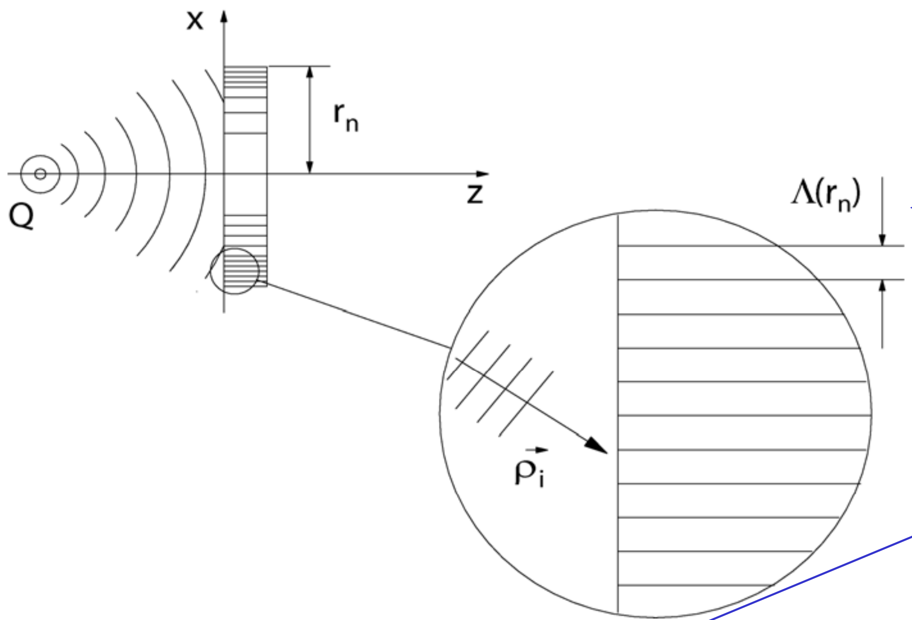
How does the “ideal” Diffractive Optic look like?
→ Volume Diffractive Optics (VDO)

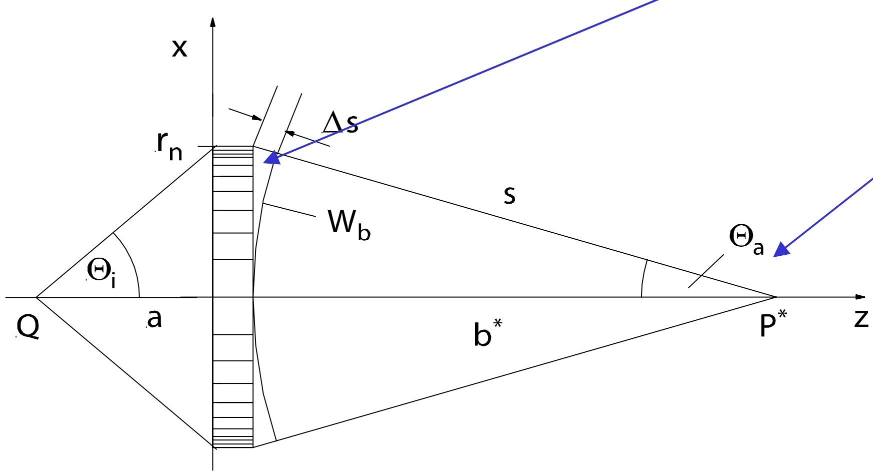
Large Aspect ratio: t/dr_n = 15,000 (WSi_2-Si, 20 keV, t = 15 um, dr_n= 1 nm)

A “ray” interacts with 420 zones ⇒ Dynamic diffraction theory



Theoretical Description of Diffraction by VDO:





1) Dynamic Diffraction Theory (N-wave CWT):

i) Decompose ZP into “locally 1D gratings”

ii) Calculate complex amplitude $A(r_n,z)$ at rear interface of ZP (e.g. N-wave Coupled Wave Theory)

iii) Reconstruct wavefront on exit pupil

2) Fourier Optics

Calculate PSF, MTF

Current limitations of approach

t << f:

20 keV, D = 20 μm, dr_N = 1 nm:

t = 13.5 μm, f = 0.5 mm, t/f $\approx$ 0.03

Borrman effect? Straight zones?

Diffraction Properties of VDO: Local Diffraction Efficiency

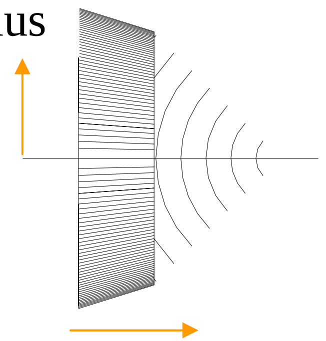
r_N = 15 um

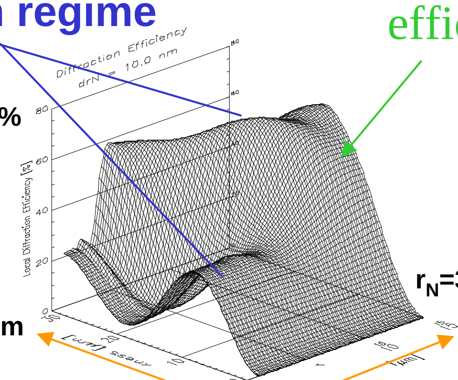
WSi_2-Si

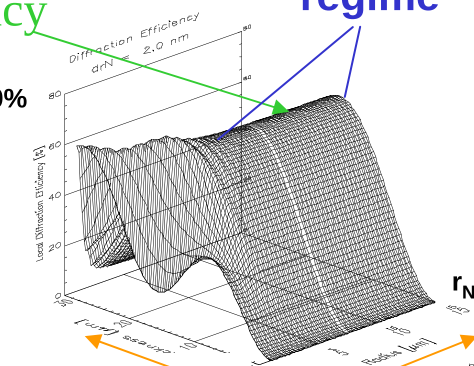
E = 19.5 keV

dr_N = 10 nm | dr_N = 2 nm

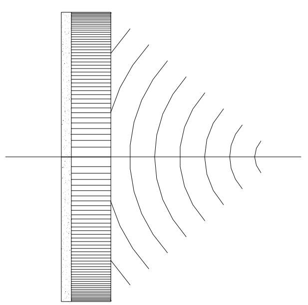
Ideal Volume Optics

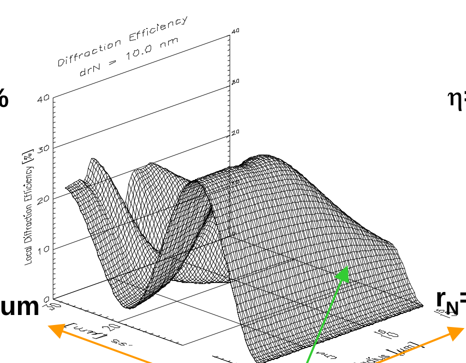


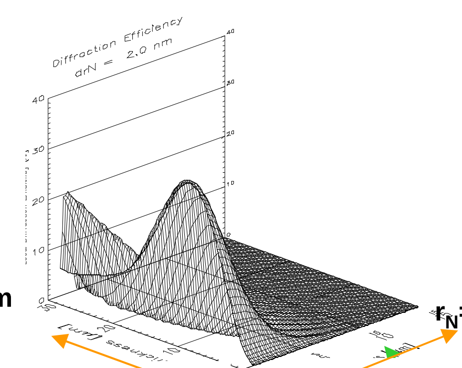




"Flat" Volume Optics

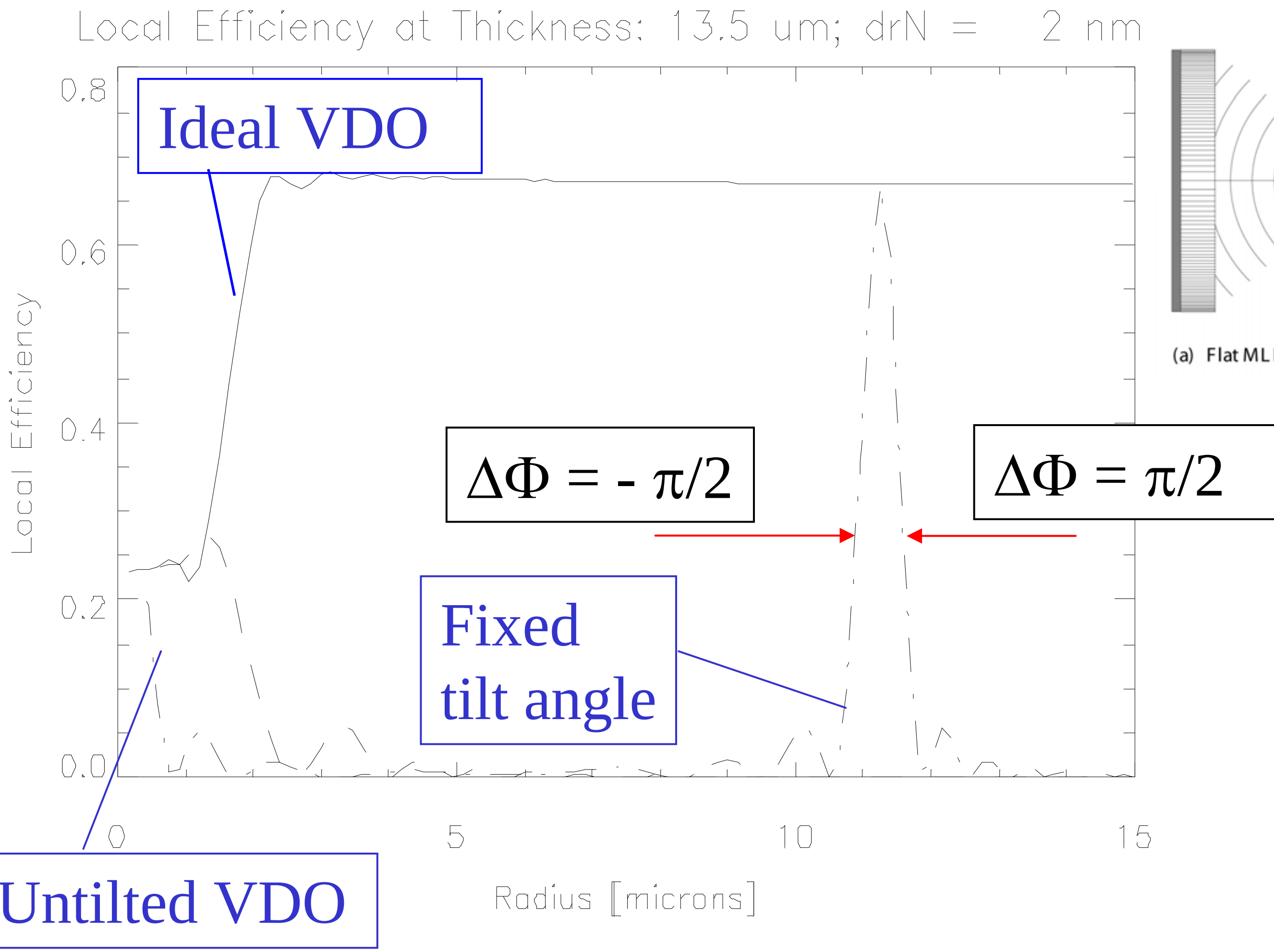


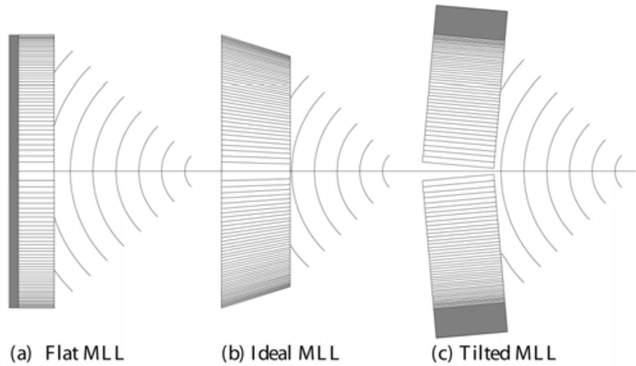




What about the phase?

WSi_2-Si, E = 19.5 keV





→ Phase changes on the order of π over small range of the aperture

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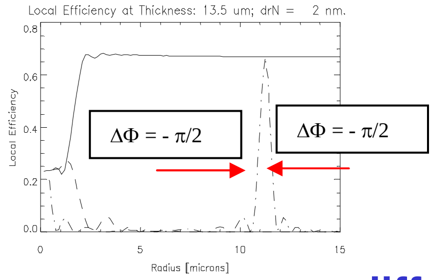
Phase Effects in Volume Diffractive Optics: Local Phase Shift

r_N = 15 um

WSi_2-Si

E = 19.5 keV



dr_N = 10 nm

dr_N = 2 nm

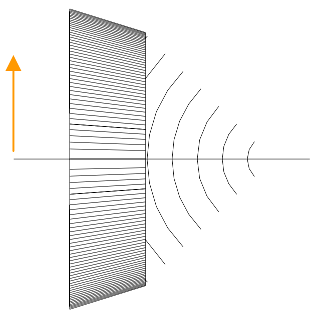
Multiwave diffraction regime

2-Wave diffraction regime

Radial phase shift - defocusing

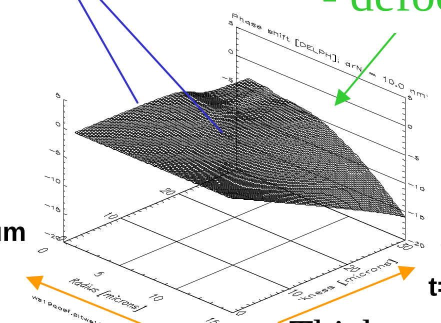
Ideal Volume Optics

Radius



Thickness

r_N=30 um

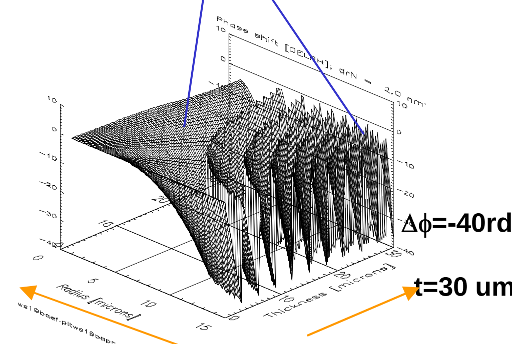


Δϕ=-20rad

t=30 um

Radius

Thickness



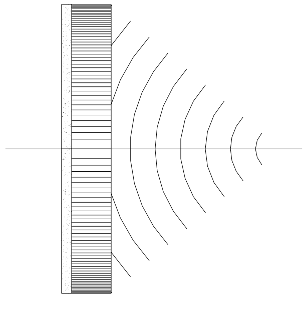
Δϕ=-40rd

t=30 um

Radius

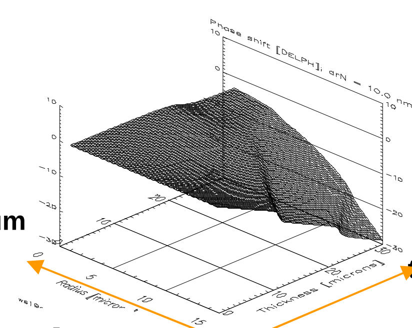
Thickness

“Flat” Volume Optics



Zone Plate

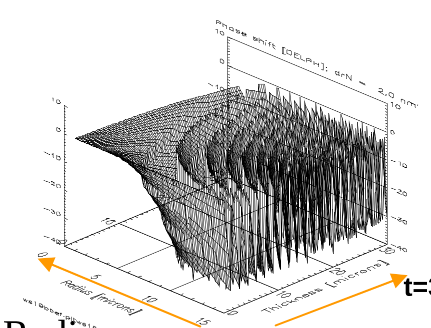
r_N=30 um



t=30 um

Radius

Thickness

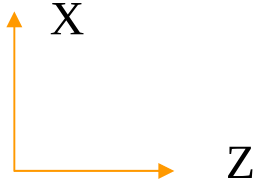


t=30 um

Radius

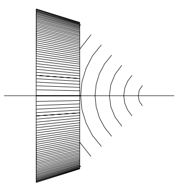
Thickness

Focusing properties of VDO

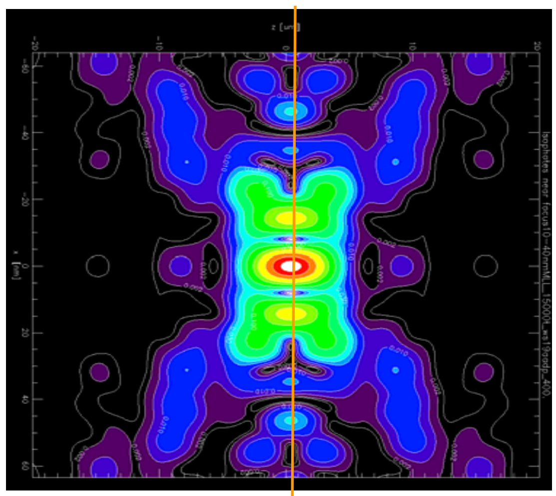


dr_N = 10 nm, t = 15 μm | **dr_N = 2 nm, t = 15 μm**

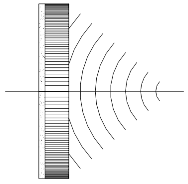
Ideal Volume Optics



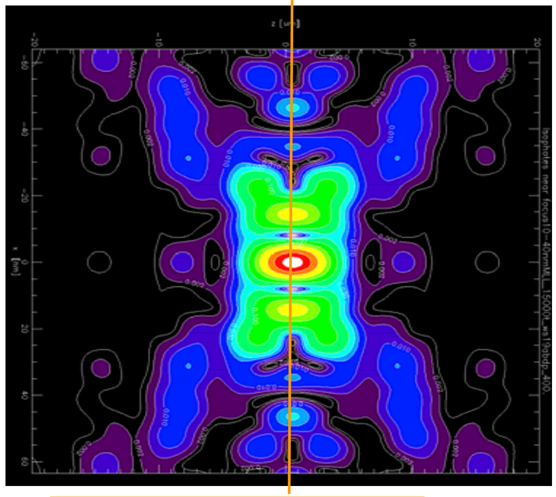
Ideal Volume ZP

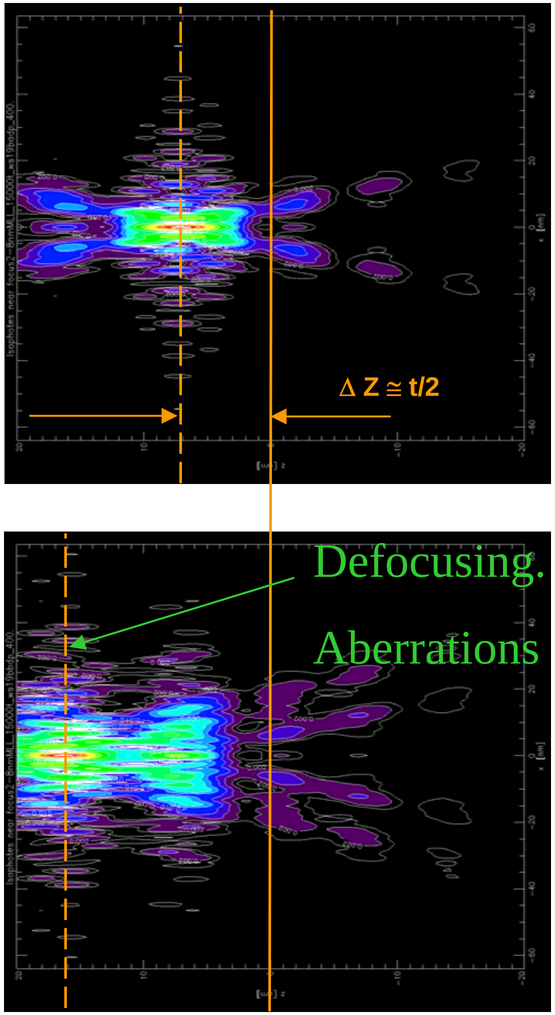


Flat Volume Optics



Zone Plate





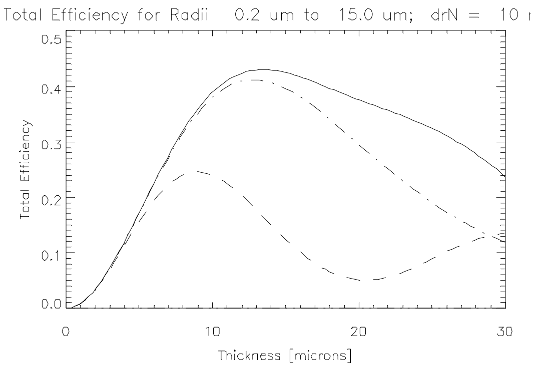
Thin-lens Focal plane

Plane of best focus

Thin-lens Focal plane

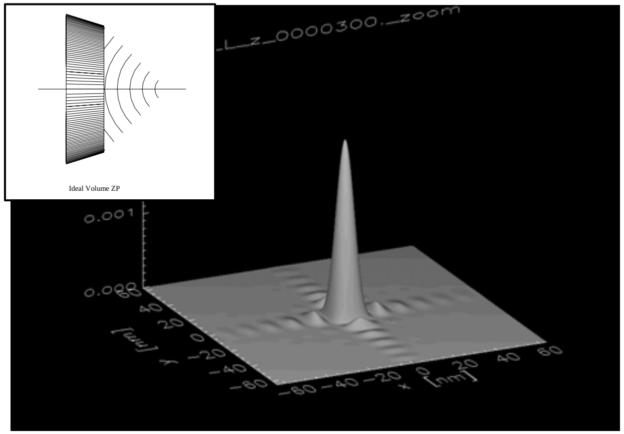
Focusing properties – PSF near focal plane

WSi_2-Si, E = 19.5 keV

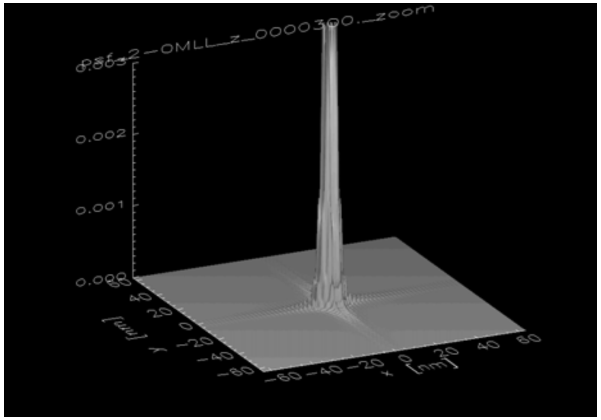


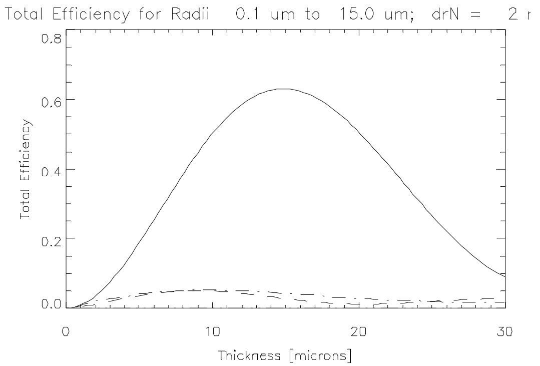
dr_n = 10 nm

dr_n = 10 nm

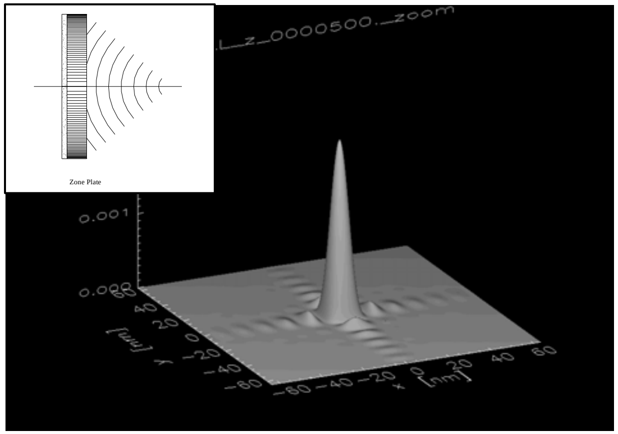


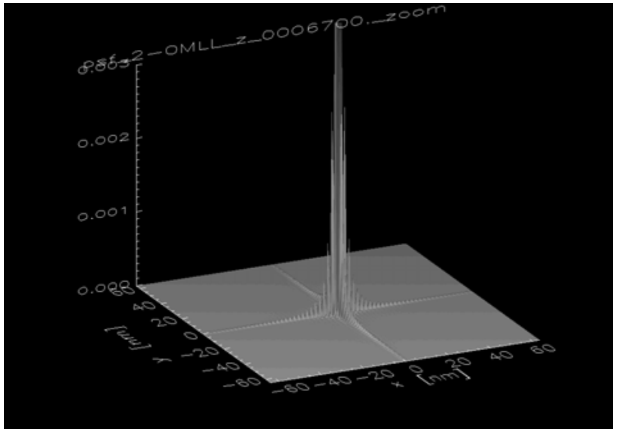
dr_n = 2 nm





dr_n = 2 nm





Total Diffraction Efficiency

Point spread function of 2D MLL, full aperture utilized

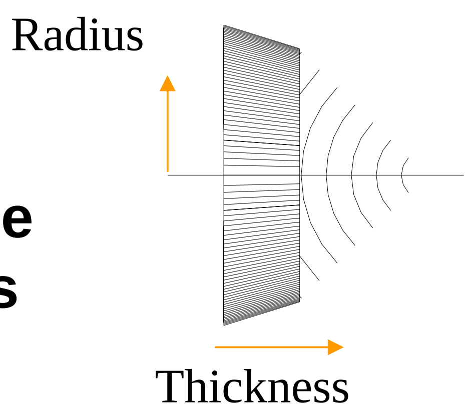
Energy Tunability of VDO

Slanting angle ψ_B: VDO optimized for energy E_0, $2d \sin \theta_B = hc/E_0$

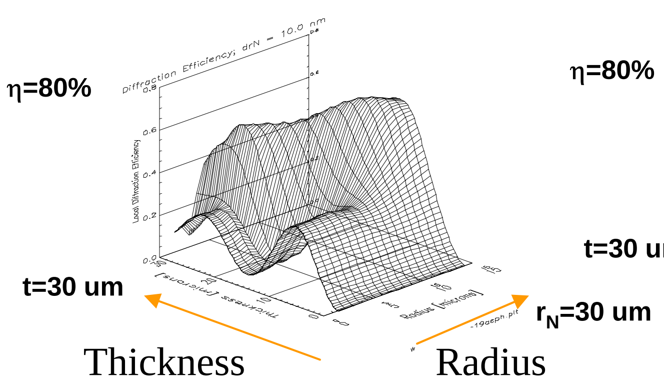
Use at different energy E' leads to deviations from the Bragg condition

r_N = 15 um
WSi_2-Si
E = 19.5 keV

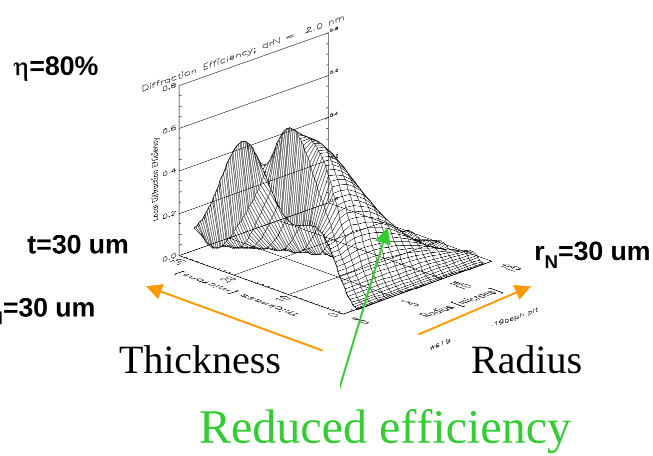
Ideal Volume Optics



dr_N = 10 nm

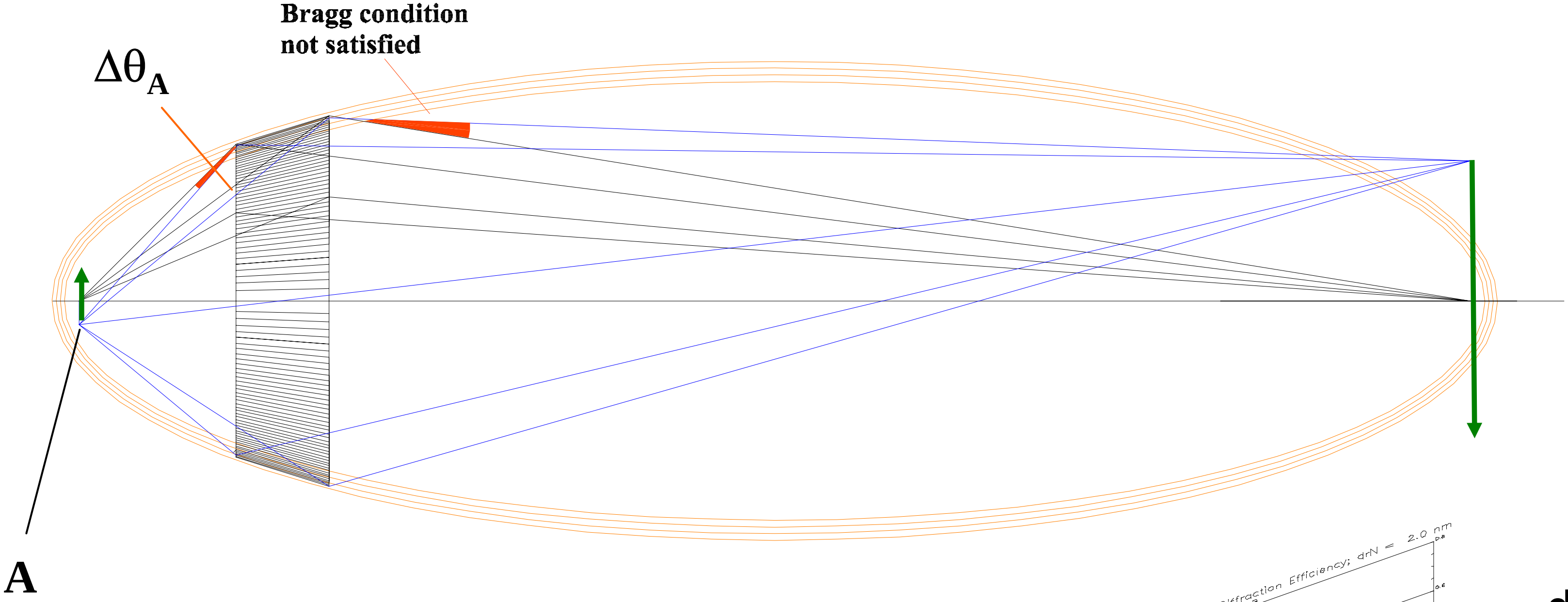


dr_N = 2 nm



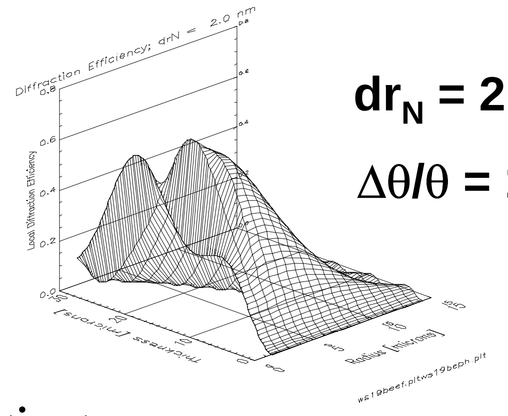
Calculation of diffraction efficiency for $E'-E_0 = 10\%$

Imaging of a large field by VDO



$$\frac{\Delta\theta_A}{NA} = 1 - {}^{A}\!/\!_{D}, \ldots, 1 + {}^{A}\!/\!_{D}$$

TXM: A/D = 0.2 – 0.5



dr_N = 2 nm,

Δθ/θ = 10%

Ideal VDO: Bragg condition satisfied for on-axis imaging

Imaging of off-axis points: Bragg condition *not* satisfied!

IV) Technical Approach to Nanofocusing: Multilayer Laue Lens

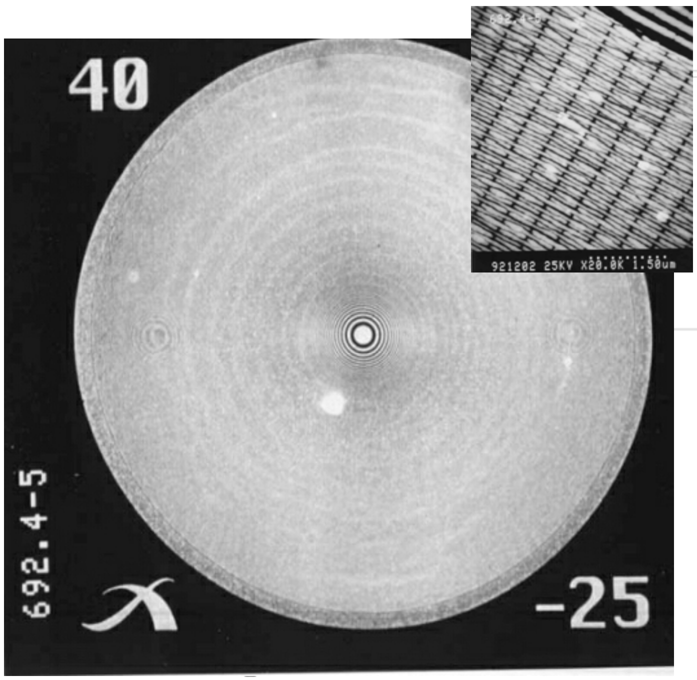
- Challenge: Manufacture High aspect ratios

Required: A ~ 1000 – 10000+

E-beam Lithography:

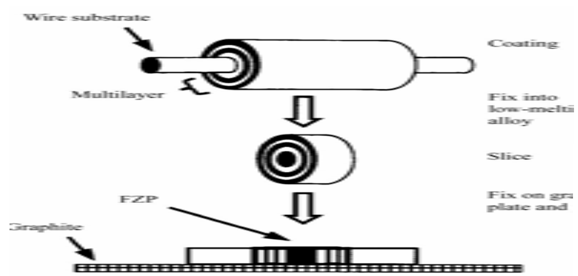
dr_N = 15 nm (CXRO)

Aspect ratio 10:1 - 20:1 feasible



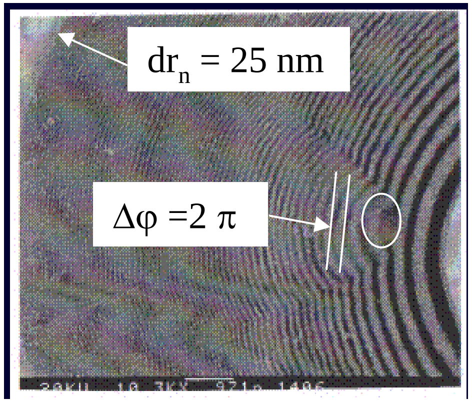
XRADIA: dr_N = 40 nm

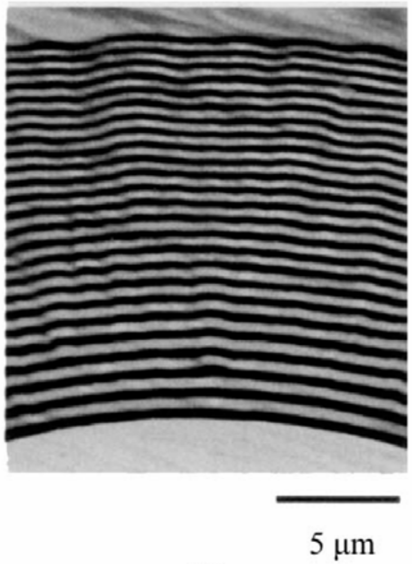
Sputtered Sliced Approach:



Kaulich, Dissertation, 1996

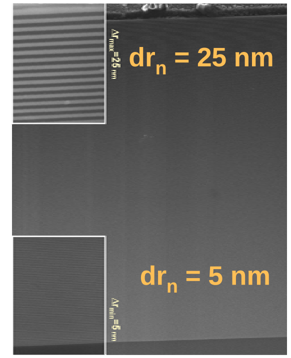
Tamura, 2002





Multilayer Laue Lens – Concept

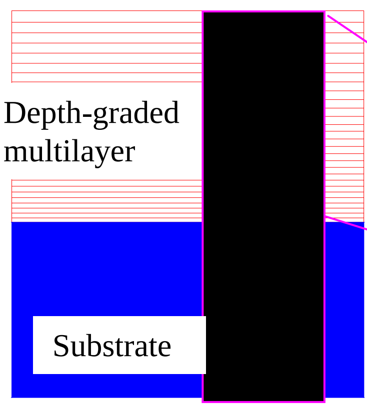
- Deposit varied depth-graded multilayer on plane substrate (thinnest structures first)
- Section to 5-20 μm depth
- Assemble into a linear MLL
- Assemble two linear MLL's into a 2D MLL.



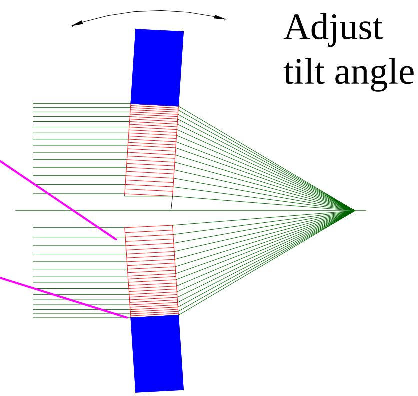
Material: WSi_2/Si

Total deposition thickness: 13.25 um

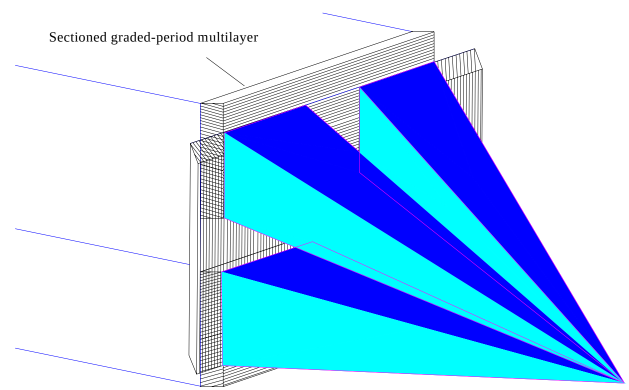
d-spacing: 5 – 25 nm



Deposited multilayer



1D MLL



2D MLL

The 43rd Anniversary R&D 100 Awards

2005 R&D 100 Award

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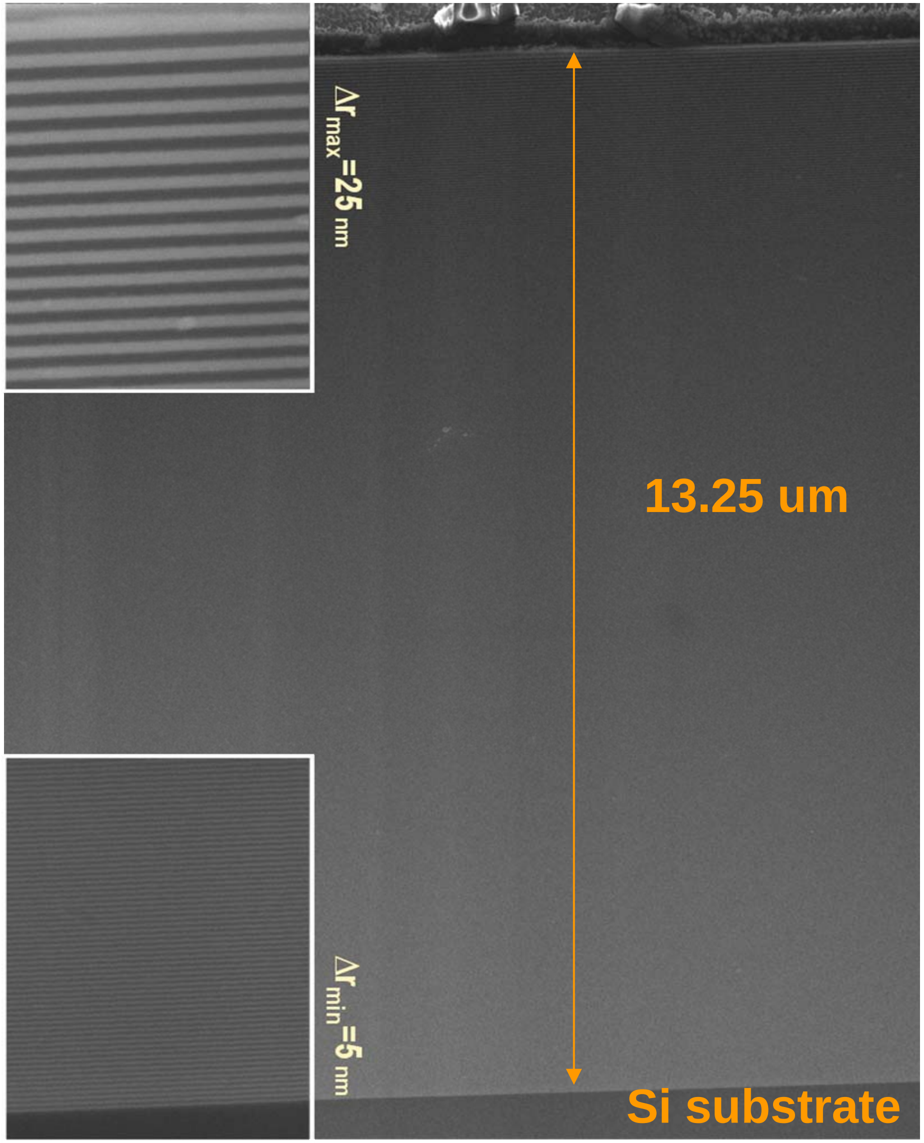
Requirements for fabrication of MLL structure

- **Parameters:**

Example for dr_N=5 nm structure:

- Material: WSi_2/Si
- dr_N = 5 nm (2d = 10 nm)
- r_n = 15 um (13.3 um deposited)
- N = 1500 (~ 1480 deposited)
- Usable aperture fraction: 44%

- **Challenges:**
  - Large deposition thickness requires low stress: → WSi_2/Si
  - High accuracy of layer placement:
    - $f = (2\, r_n/\lambda)\cdot dr_n(r_n)$
  - Thinning/Polishing: avoid distortions of structure



X-ray focusing with MLL sections, dr_N = 15, dr_N = 10 nm

Sample A: dr_N = 15 nm

Sample B, C: dr_N = 10 nm

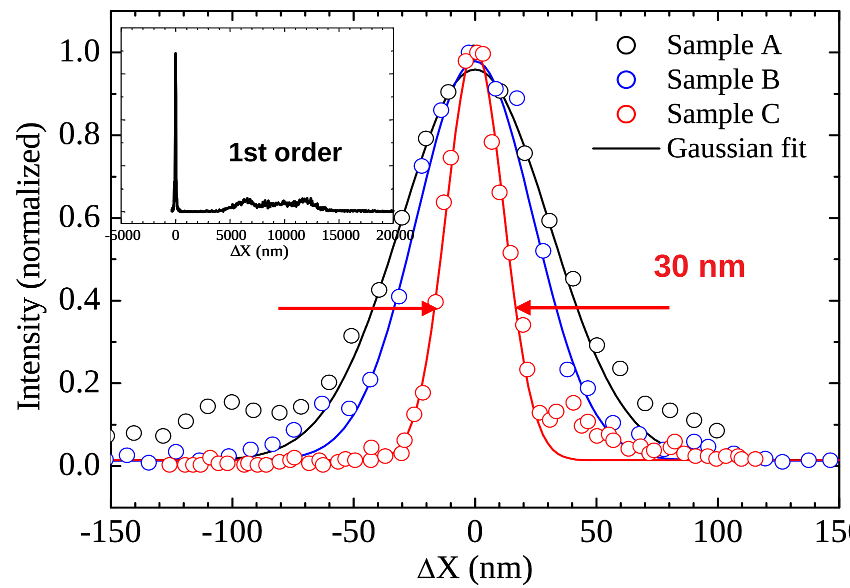
NA-limited resolution:

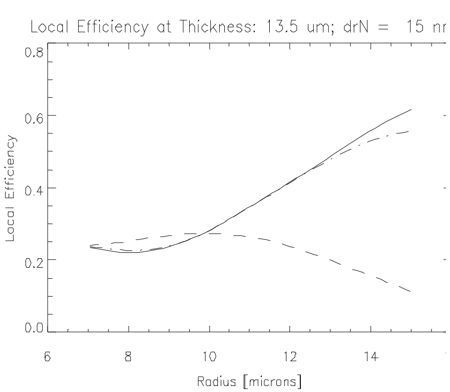
Sample A: 57 nm (27% NA)

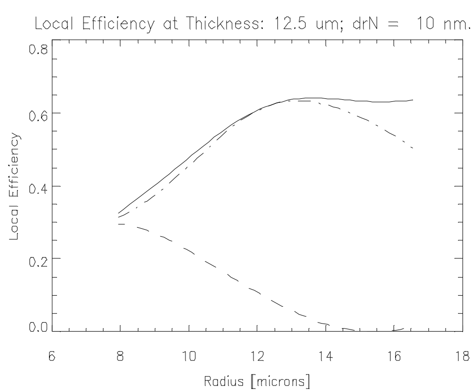
Sample B: 44 nm (23% NA)

Sample C: 24 nm (41% NA)

Resolution measurement







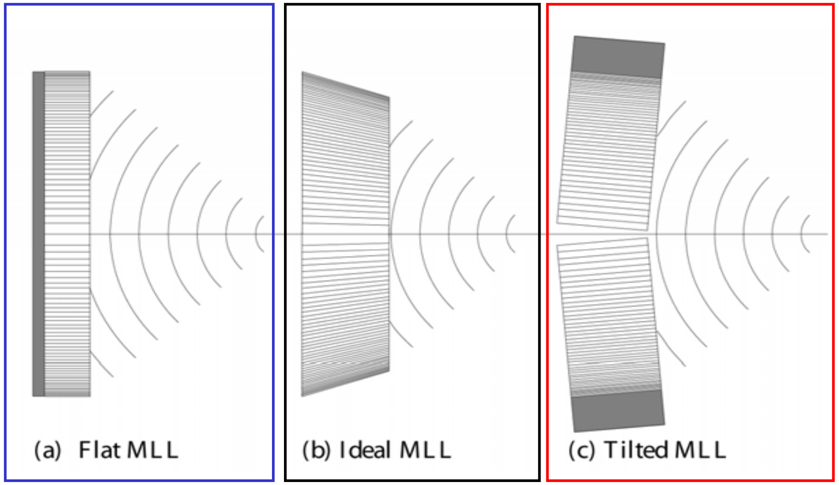
Photon Energy: 19.5 keV

Measured Resolution: **30 nm**

Diffraction Efficiency: **44%**

Kang et. al, PRL, Apr., 2006

Where is the resolution limit for x-ray focusing (Diffractive Optics)?



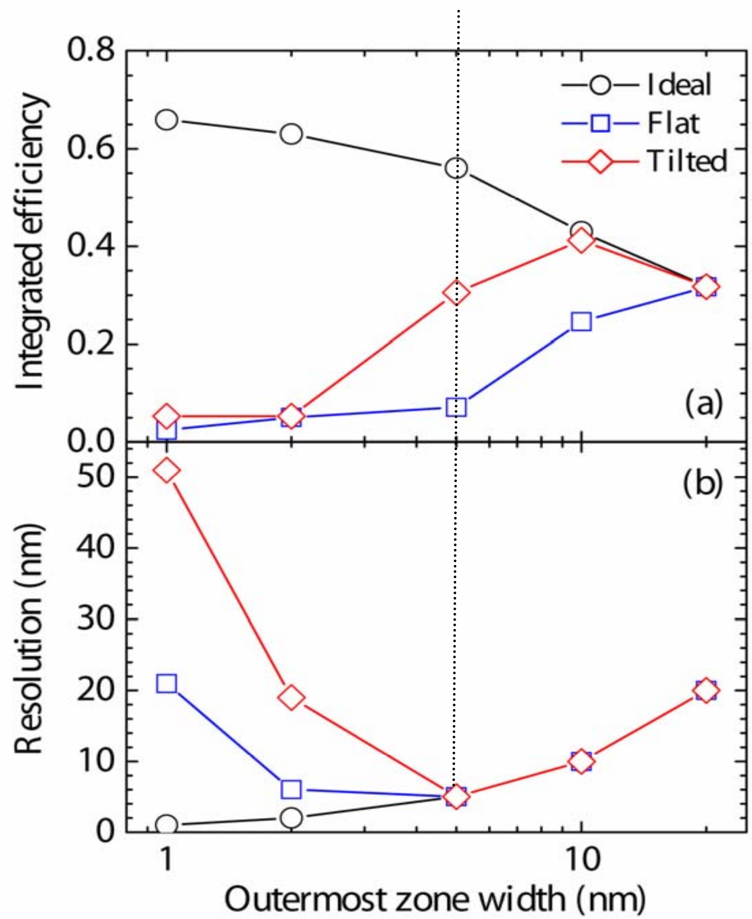
- Ideal structure:
  - Resolution approaching 1 nm feasible,
  - Diffraction efficiency (2D) > 50%
- Tilted MLL: δ = 5 nm feasible

- Locally 1D CWT valid to ~ 1 nm

- What is the effect of Borrman-Fan on Phase?

- When is curvature of zones required?

Calculations for 1D MLL



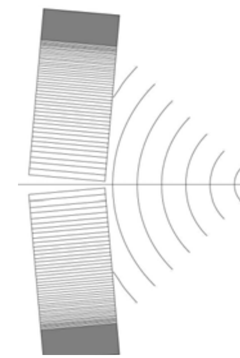
Kang et. al, PRL, 2006

V) Summary: Towards Nanofocusing of Hard X-rays.

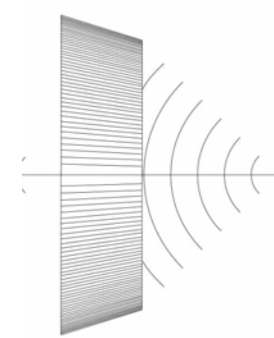
- Diffractive x-ray optics are capable of focusing x–rays to one nanometer or below.
  - Dynamic Scattering → Satisfy Bragg condition
  - Small Energy bandpass
  - Large acceptance: ok
  - Good Focusing efficiency: ok
  - Full-Field imaging: not for $\delta <\approx 5$ nm

- Multilayer Laue Lenses offer a feasible path towards true nanofocusing
  - <u>'Tilted' MLL</u> approach provides $\delta_R \sim 5$ nm, <u>'Ideal' MLL</u> < 5 nm
  - Materials System: WSi_2/Si
  - Accurate depositioning of ≈1500 zones, total deposition thickness > 10 μm
  - Sectioning/polishing to thickness of 5 um – 30 um
  - Achieved: <u>line focus of 19.5 nm</u>, E = 19.5 keV, 33% efficiency.

- Next steps:
  - toward 6 nm focus: engineering of 2D focusing structure (4 MLL sections)
  - Ideal structures required for < 5 nm focusing (5+ years?):
    - *Radial change of slant - R&D ongoing (Macrander, Liu, Conley)*
    - *<u>Very significant engineering challenges to come ($$$...)</u>*



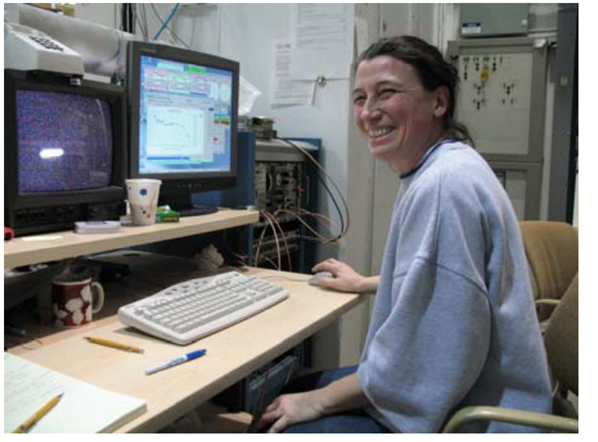
Tilted MLL



Ideal MLL

Acknowledgments

- Beamline staff, APS sector 12-BM, 8-ID-E



- DOE, BES, under Contract No. W-31-109-ENG-38.
- *ANL-LDRD, 2003-242-R1*
- *ANL-LDRD, 2006-225-N0*