Multilayer Laue Lens-A Type of X-ray Nanofocusing Optics: Status, Progress and Prospects

NSLS-II Project

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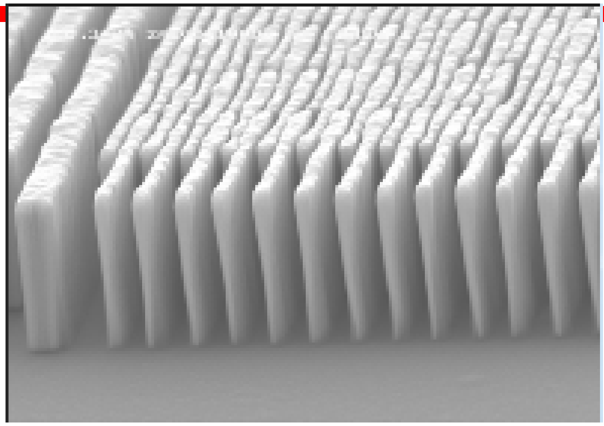
Overview of x-ray focusing optics

- Reflective optics
  - Waveguide, capillary, K-B mirror w/o multilayer
  - Achieved: ~25 nm
  - Hard limit: ~ 10 nm
- Refractive optics
  - Compound refractive lenses (CRLs): ~ 10 nm
  - Adiabatically focusing lenses (AFLs): no hard limit, but has practical limit for nanofocusing
  - Achieved: ~50 nm
- Diffractive optics
  - Fresnel zone plates (FZPs): fabrication limit
  - Multilayer Laue Lenses (MLL's): no hard limit, suitable for hard x-ray focusing
    - Achieved line focus: ~17 nm
    - Promising for true nanometer focus
- Kinoform lenses, multilayer mirrors

Fresnel Zone Plate



http://www.xradia.com/Products/zoneplates.html

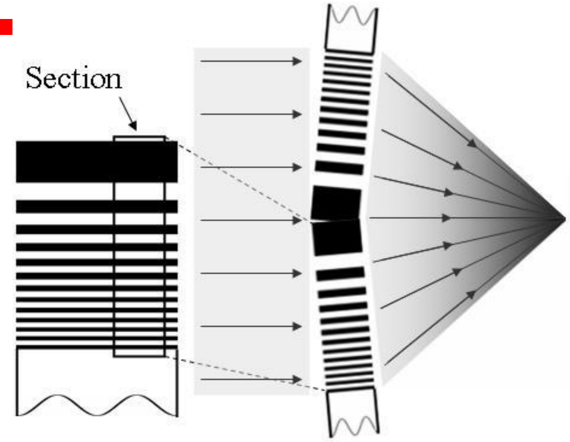
Lithography method:

- >15 nm zone width
- <30 aspect ratio

Limited resolution and efficiency for hard x-ray focusing:

Au, w=300 nm, efficiency=15% @ 1 keV; 0.3% @ 30 keV

Multilayer-Laue-Lens (MLL)



1-D structure allows fabrication via thin film deposition techniques

- limitless aspect ratio
- very small zone width

MLL's are capable of achieving nanometer focus with high efficiency

H. C. Kang et al., Phys. Rev. Letts. 96, 127401 (2006).

Challenges for 1-nm optics

- Fabrication challenges
  - Right choice of materials for minimum build-up stress
  - Long-term machine stability
  - Nanometer accuracy over tens microns radius and tens thousands of layers’ deposition
  - Increasing difficulty in fabrication for larger numerical aperture
- Theoretical challenges
  - Full wave theory (geometrical theory fails)
  - Large numerical aperture (paraxial approximation fails)
  - Dynamical diffraction (multiwave scattering effect)

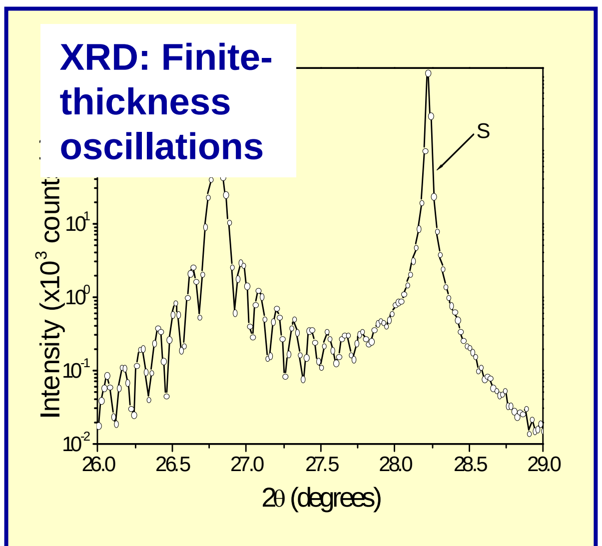
MBE Method for MLL Fabrication

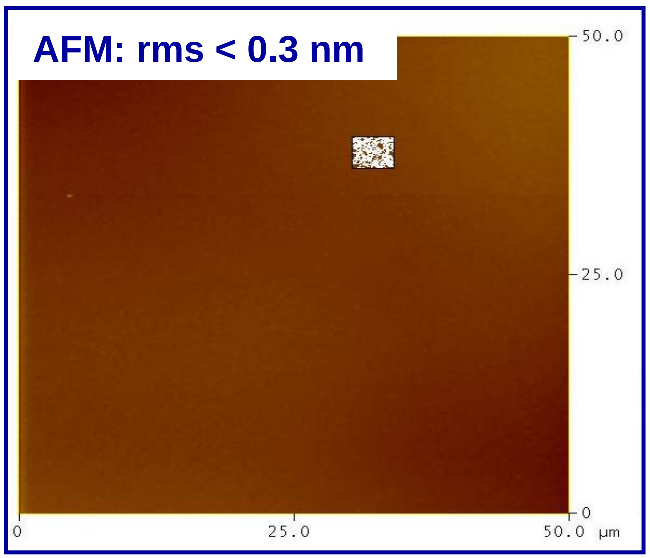
The challenge: maintain < 1nm precision in > 10μm thick film

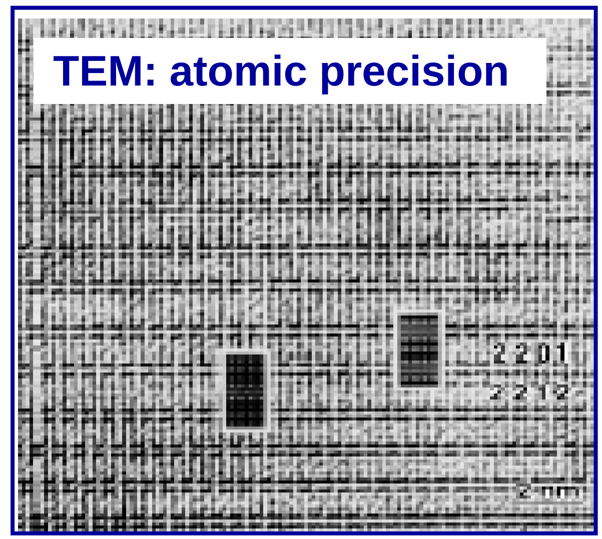
Our approach: We plan to construct a new MBE chamber custom-designed for long runs and thick films. It might include off-axis sputtering or PLD for deposition of the thickest sub-layers.

MBE has already demonstrated precision much better then 1 nm:

[Sputtering and pulsed laser deposition are typically an order-of-magnitude less precise.]







(a) LaSrCuO film on LaSrAlO substrate; (b): BaBiO film; (c): BiSrCaCuO superlattice

Theoretical Questions

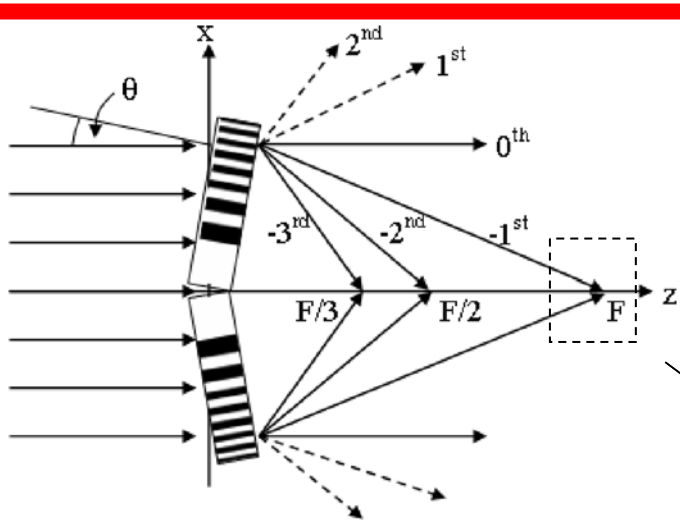
- Where is the limit for x-ray focusing optics?
- What kind of x-ray optics is needed to achieve 1-nm focusing?
- How can we optimize the performance of the optics?
- What's the effects of imperfections on x-ray focusing optics?

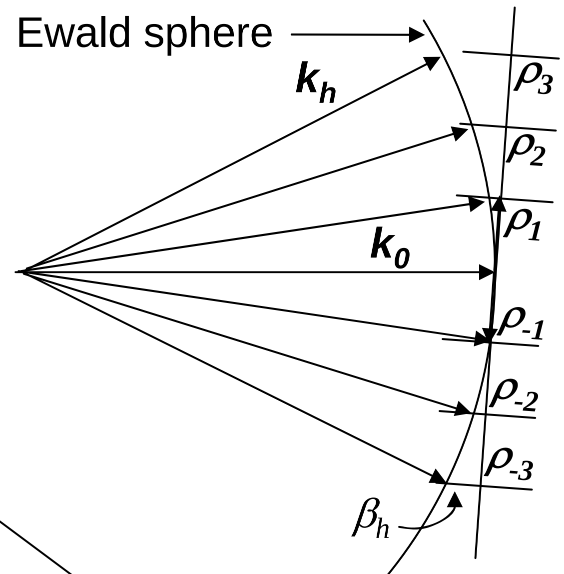
Theoretical Modeling Approaches

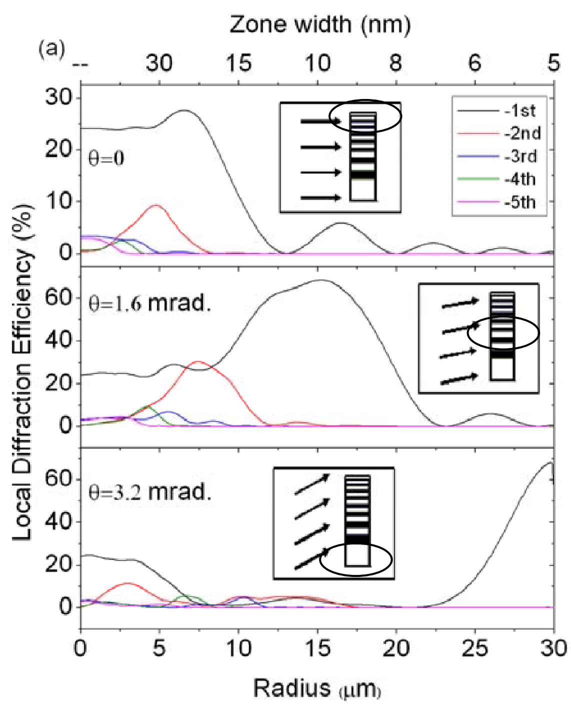
- Localized one-dimensional theory
  - Decompose MLL into local periodic gratings.
  - Limited to Δr_n~1 nm and w (thickness) <<f (focal length).
- Parabolic wave equation
  - Paraxial approximation, only valid for small NA
- Takagi-Taupin description of dynamical diffraction
  - Full wave theory
  - Spans the diffraction regimes applicable to thin gratings and crystals
  - Applicable to arbitrary zone profile
  - Not limited to small NA
  - The effect of roughness needs to be included (roughness comparable to the zone width)

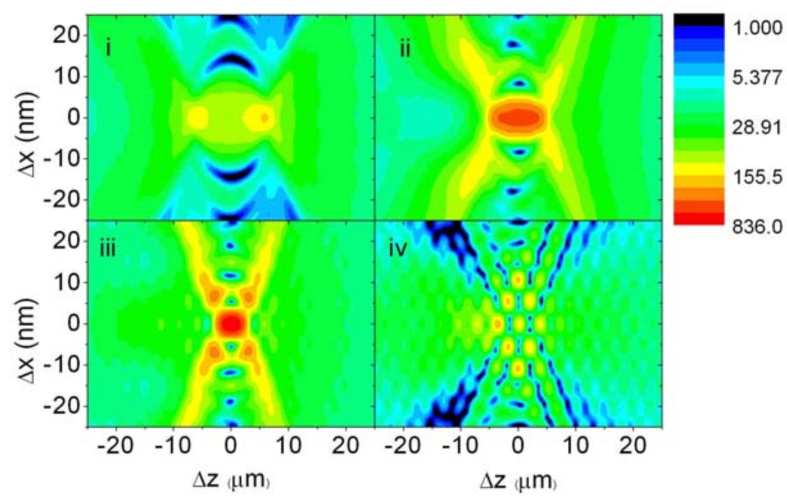
H. Yan et al, Phys. Rev. B 76, 115438 (2007)

Diffraction from MLL with Flat Zones







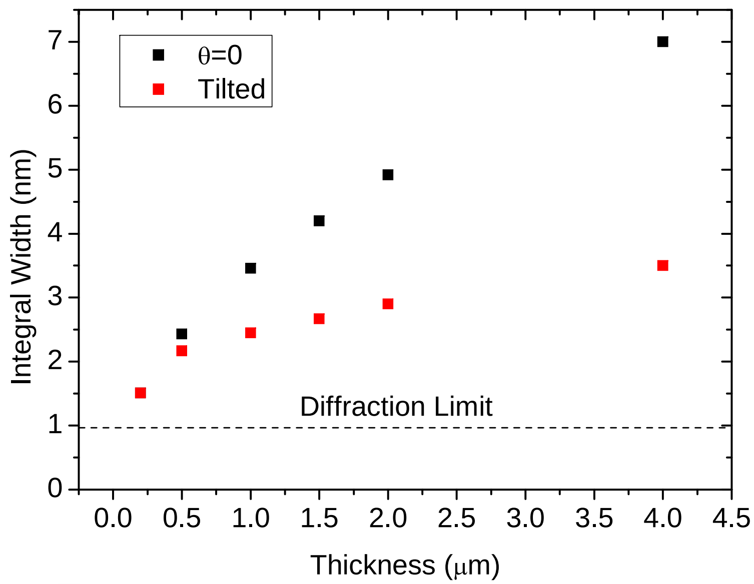


Trade-off between efficiency and effective NA

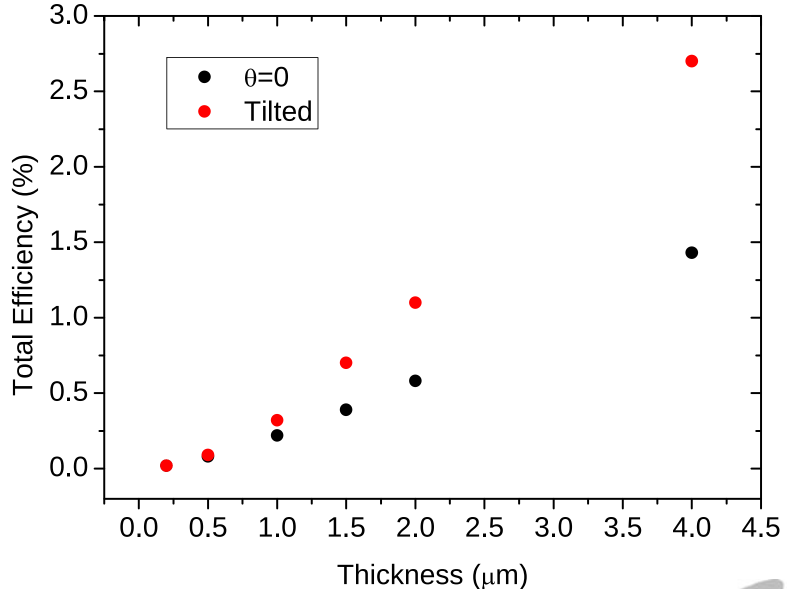
- Geometrical theory becomes valid when the lens is thin enough and diffracts not “dynamically”.
- In geometrical theory, physical NA = effective NA

Example: MLL with flat zones and outmost zone width of 1 nm

Focal size



Total Efficiency



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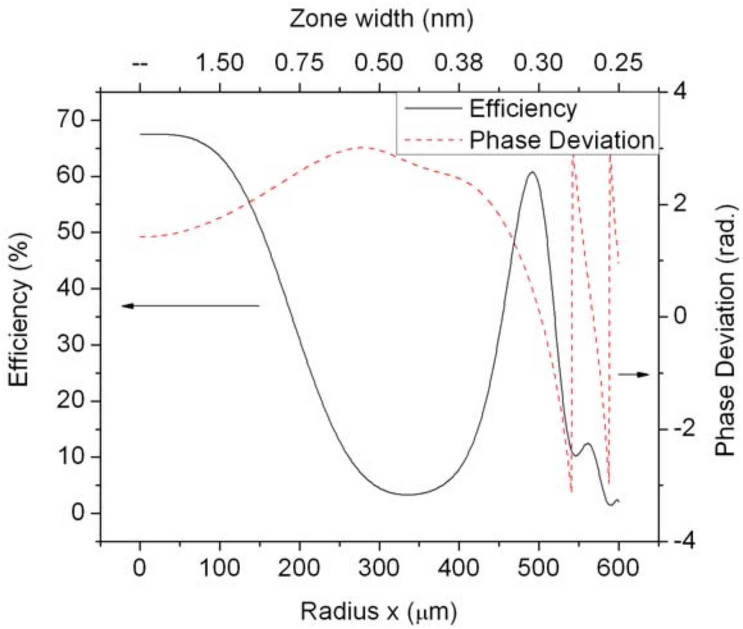
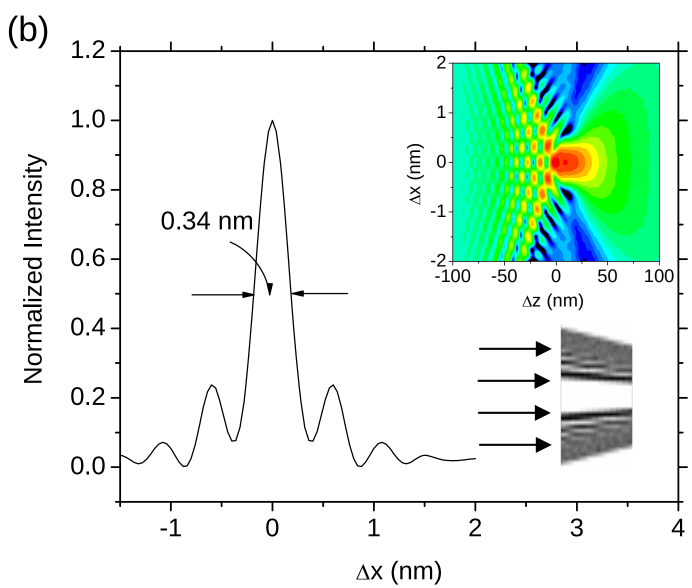
Can we achieve high efficiency and large effective NA simultaneously?

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

$$x_n = a(z)\sqrt{n\lambda f + n^2\lambda^2/4}$$

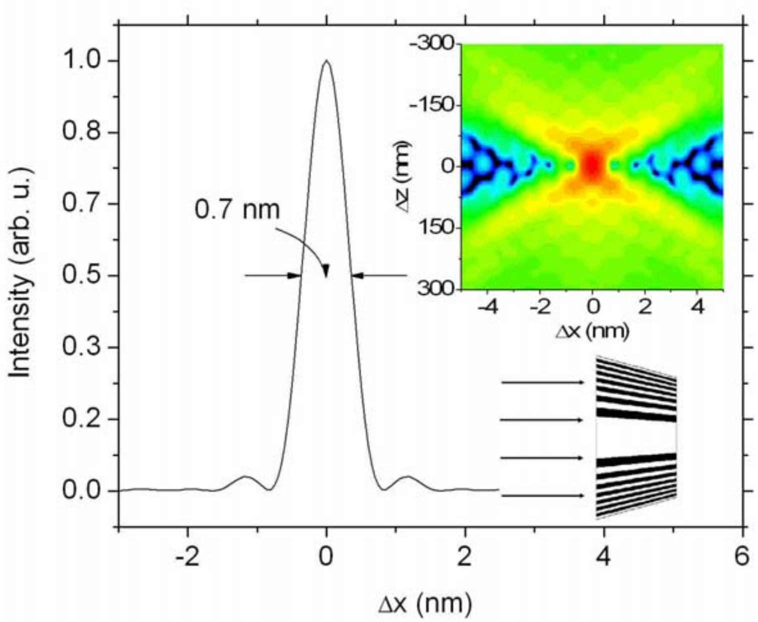




Still not ideal structures!

Summaries about MLL method

- No hard theoretical limit prevents hard x-rays from being focused to 1-nm by MLL method.
- Using MLL's with flat zones, 1-nm focus can be achieved if the lens is thin enough, but the efficiency maybe become too low to be useful.
- To achieve 1-nm focus and high efficiency, wedged MLL's are required.

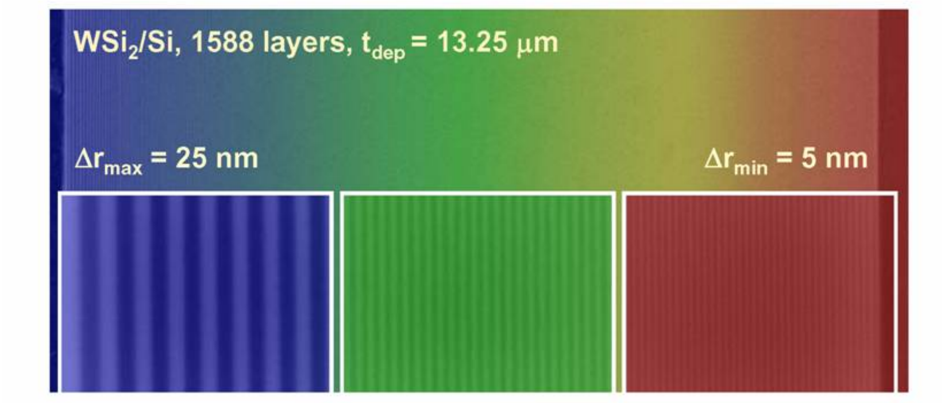


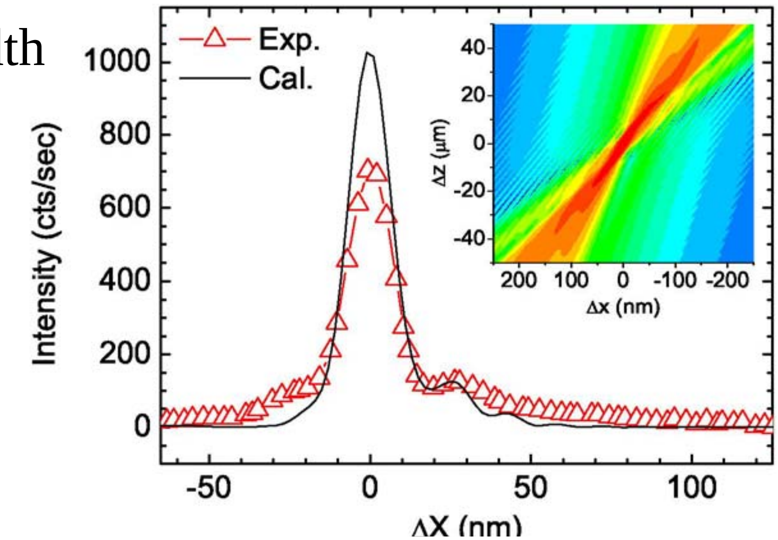
Wedged MLL, 0.75 nm outmost zone width, WSi_2/Si, energy at 19.5 keV.

FWHM=0.7 nm, total efficiency=50%

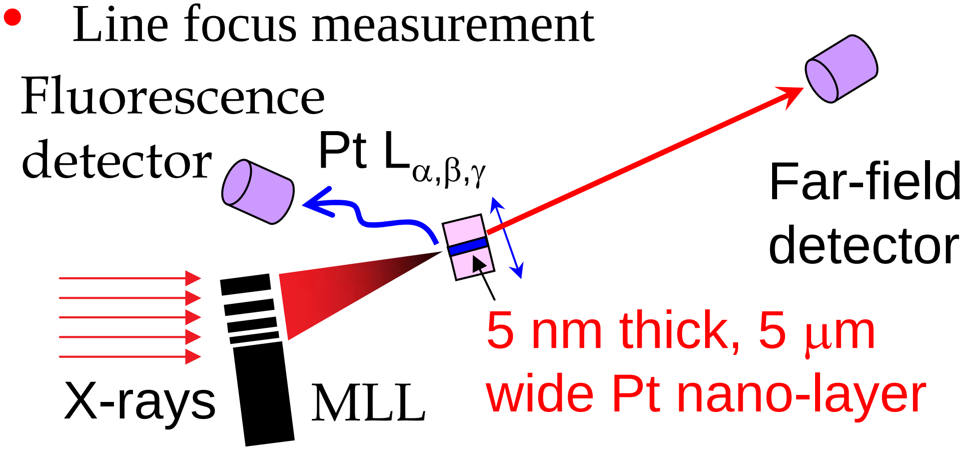
Experimental Achievement at APS

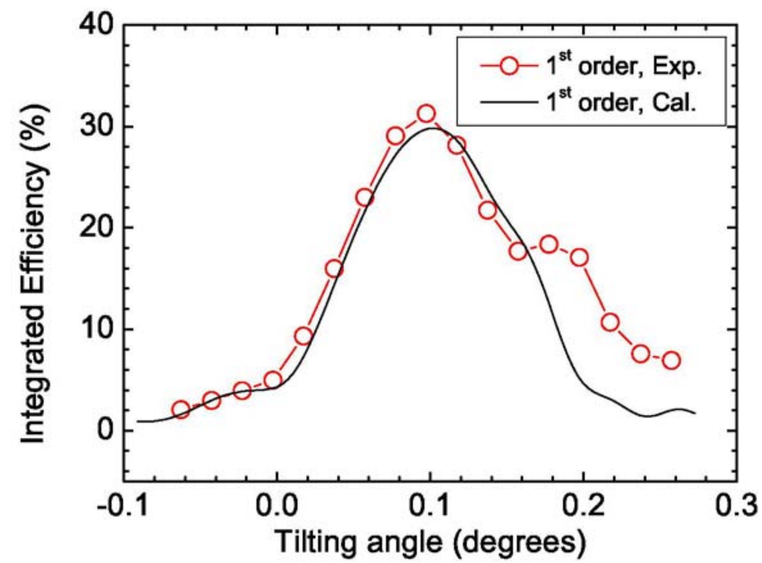
- 40% of full structure, 5 nm outmost zone width





- Line focus measurement





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

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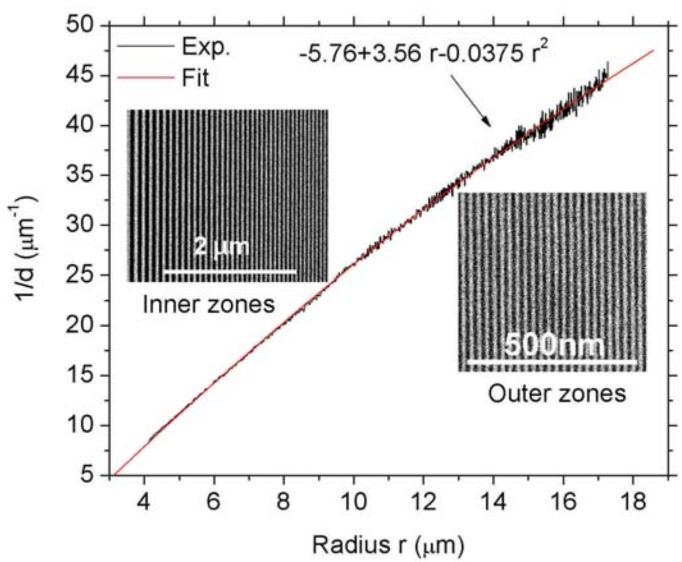
Other Characterization Methods

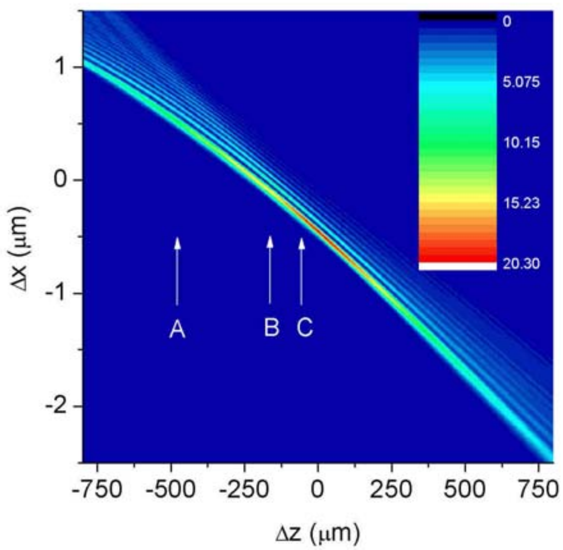
- For direct focus scan, alignment is difficult and time-consuming.
- We are developing other complimentary characterization methods
  - Simulation aided method
  - Diffracted wavefront imaging by crystal diffraction
  - Phase retrieval method for wavefield reconstruction at the focal plane

Simulation aided characterization

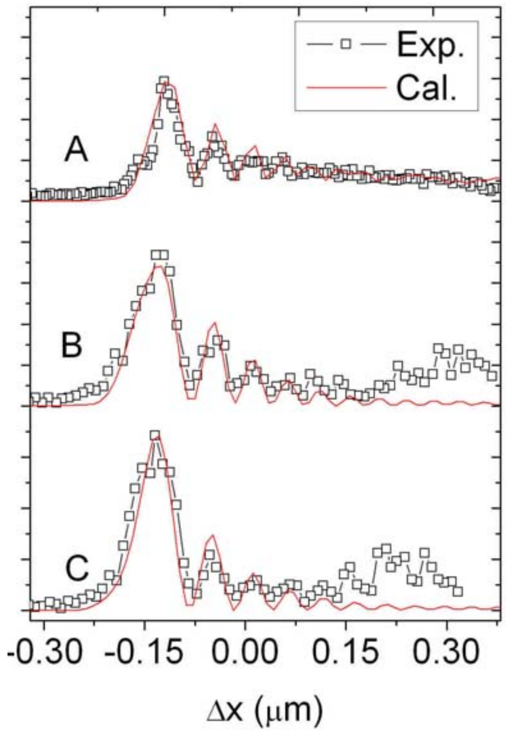
Actual zone profile



Calculated intensity isophote pattern



Comparison



H. Yan, H. C. kang, J. Maser et al., Nuclear Inst. and Methods in Physics Research, A , in press

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Progress in MLL's fabrication at APS

- Periodic multilayers with 0.7 nm thickness (WSi_2) have been fabricated by sputtering at APS
- Initial wedged structure has been fabricated at APS for conceptual demonstration.

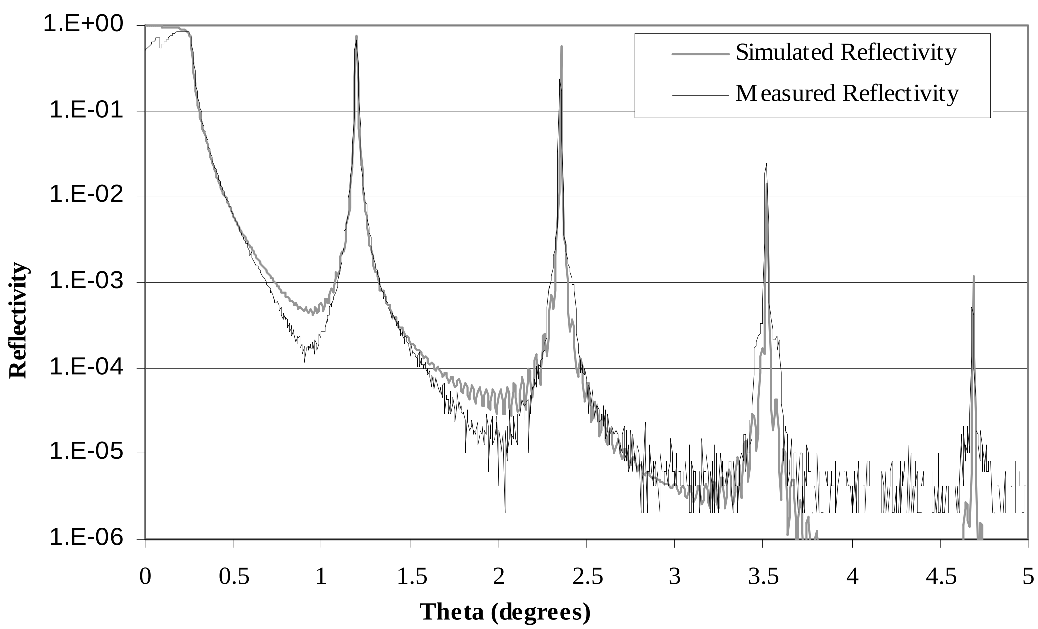
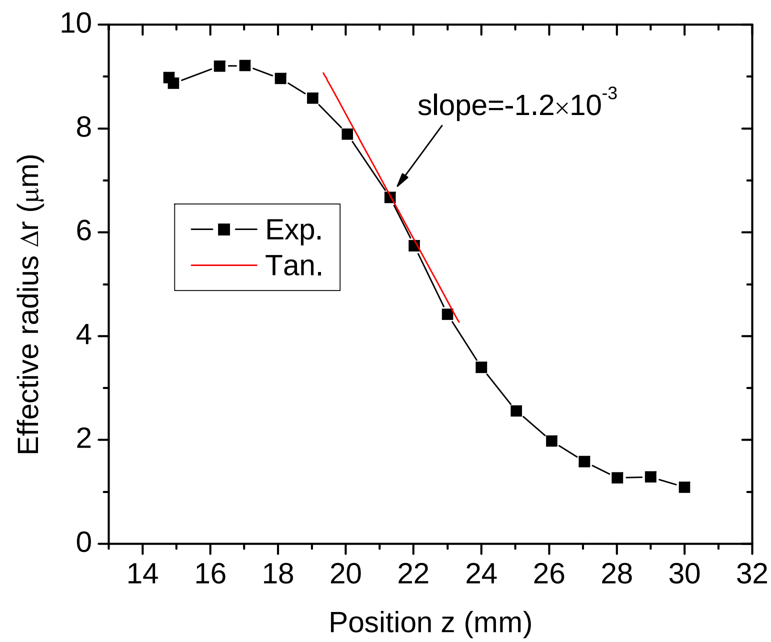


Fig. 4. Reflectivity measurement at 8 keV for narrow bandpass applications. 400 bilayers WSi_2=7.2 Å, Si=30.8 Å, 14 Å SiO_x native surface oxide.



R. Conley/APS

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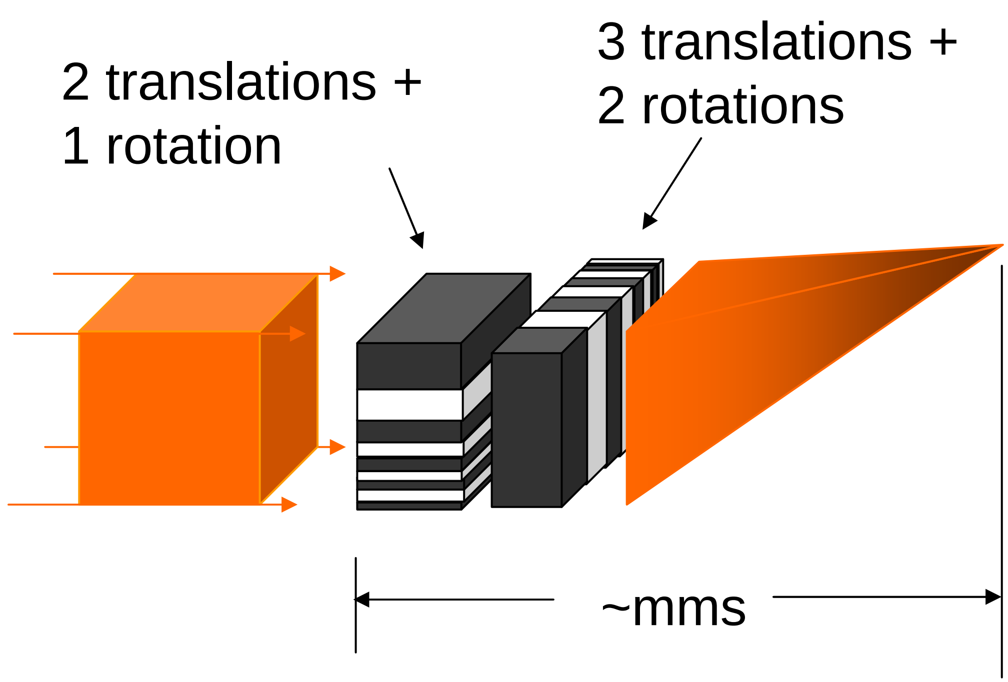
Progress in 2-D point focusing by crossed MLL's at APS



Initial design for the prototype has been completed and the instrument is under test.

D. Shu, H. Yan and J. Maser/APS

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MLL Development at BNL

- Adopt the mature sputtering techniques developed at APS for inner zones growth of MLL.
  - Near term issues: hiring deposition scientist, deposition instrument
  - Current sputtering techniques are capable of fabricating 5-nm or better optics

- Explore single crystal approach for MLL (MBE)
  - Slower growth rate
  - More accurate control on zone with and smoother interface, suited for the growth of outer zones
  - Developing techniques for wedged structures

Milestone & Timeline for 1-nm Using MLL

FY08

- Deposition scientist hired; deposition machine installed and tuned
- Start MLL fabrication
- Theoretical development for roughness study completed

FY09

- Fabricate and test MLL's for <10 nm focus
- Explore MBE method for MLL fabrication
- Develop metrology capable of determining zone width and placement to <1nm resolution.

FY10

- Fabricate and test MLL's for <5 nm focus

FY11

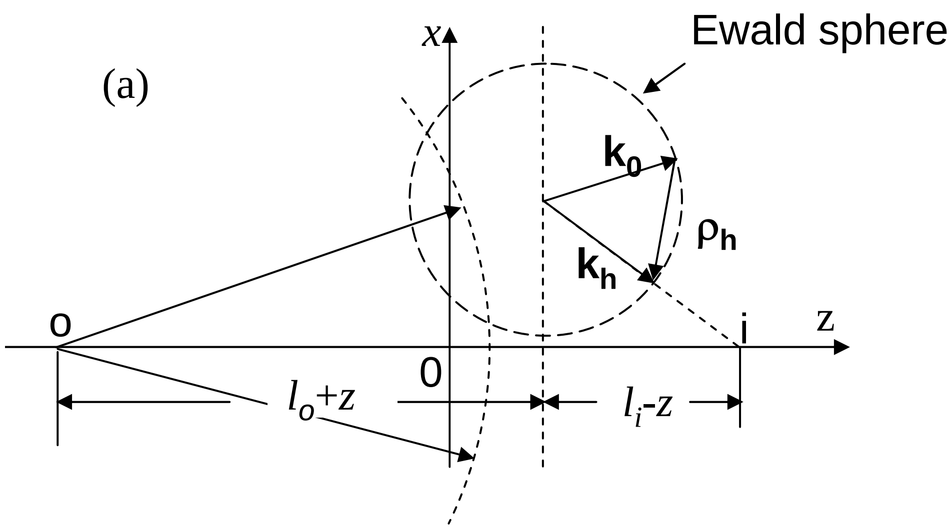
- Continued R&D effort for 1-nm optics
- Design and construct the prototype device for 1-nm spatial resolution

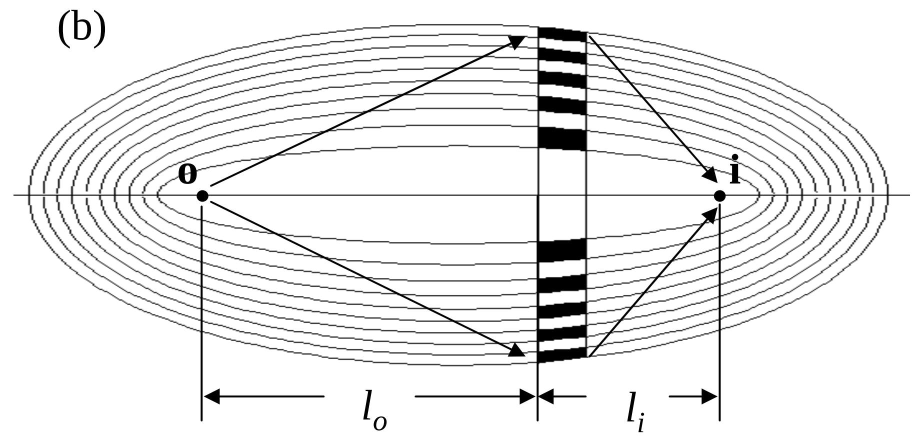
FY12

- Test the prototype device for 1-nm spatial resolution

What are the ideally structures to focus x-rays?

- Bragg condition is satisfied everywhere to achieve high efficiency. $\beta_h = 0$
- All diffracted waves add up in phase at the focal point.





Zone plate law: $$\frac{4x_n^2}{n^2\lambda^2/4 + n\lambda(l_o + l_i)} + \frac{4[z + (l_o - l_i)/2]^2}{(n\lambda/2 + l_o + l_i)^2} = 1$$

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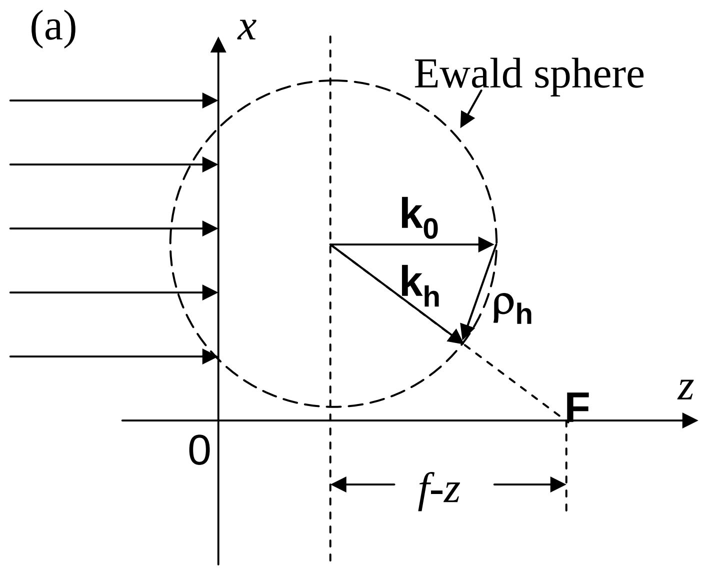
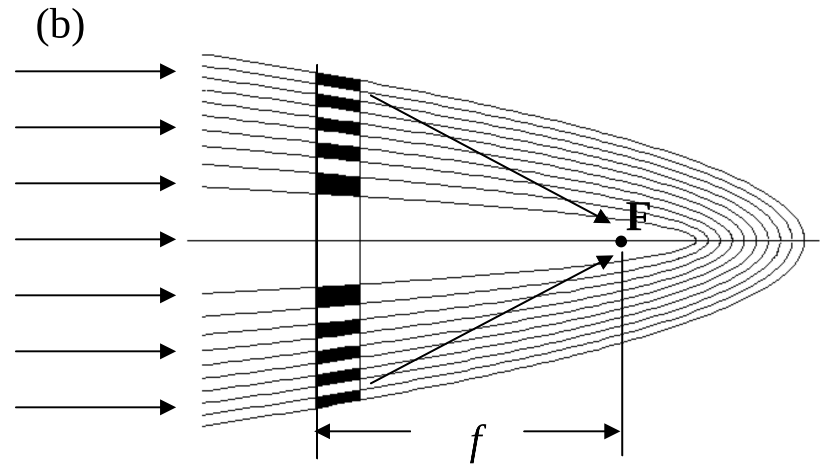
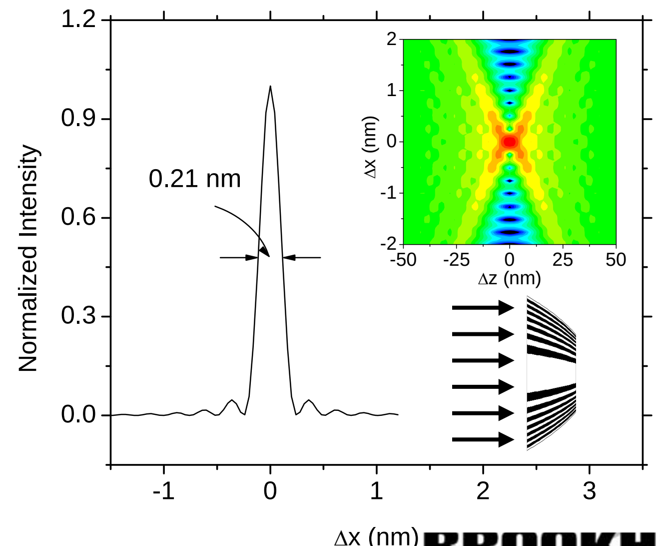
Incident plane wave





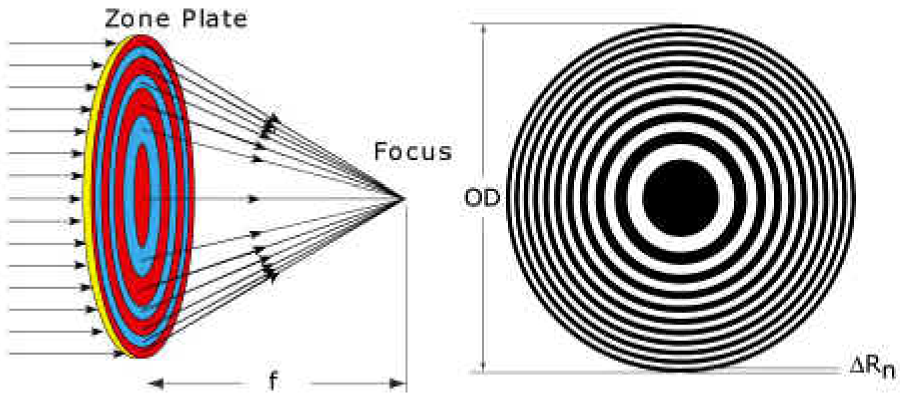
Outmost zone width: 0.25 nm



Zone plate law:

$$x_n^2 = n\lambda(f - z) + n^2\lambda^2 / 4$$

Dynamical Diffraction Theory is Needed!



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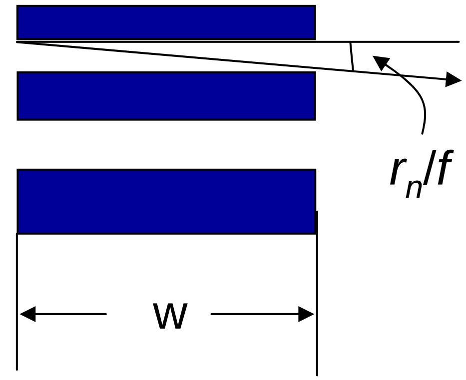


Geometrical-Optical theory:

Zone plate law: $r_n^2 = n\lambda f + n^2\lambda^2/4$

Zone width: $\Delta r_n = \frac{\lambda f}{2r_n}\sqrt{1+\frac{r_n^2}{f^2}}$

Resolution limit: $1.22\Delta r_n / m$

Optimum thickness: $w = \frac{\lambda}{2\Delta n}$
(phase zone plate)

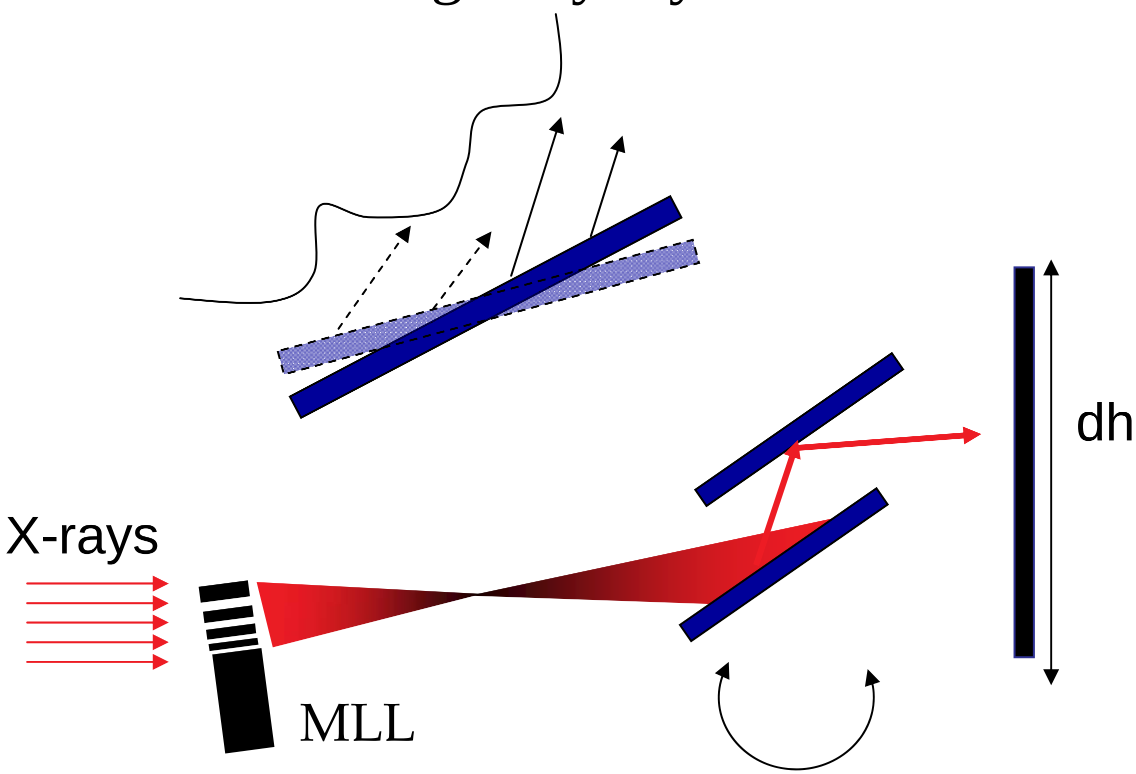
For the geometrical-optical theory be valid, the zone plate has to be "thin" so that the multiwave scattering (dynamical) effect can be ignored.

$$w < \frac{\Delta r_n}{r_n / f} \approx 2\frac{\Delta r_n^2}{\lambda}$$

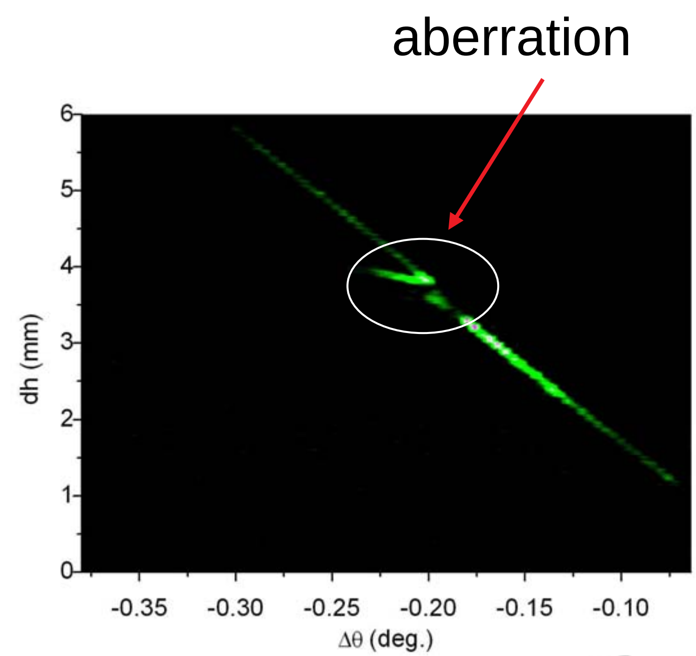
At optimum thickness, dynamical diffraction properties begin to dominate when the outmost zone width becomes smaller than ~ 10 nm!

Diffracted wavefront imaging by crystal diffraction

- A curvature of the diffracted wavefront corresponds to a directional change of the propagation direction.
- Very small directional change of propagation at different place can be imaged by crystal diffraction



Phase gradient – space map



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