De-mystifying Kinoforms; Can we go below 10nm?

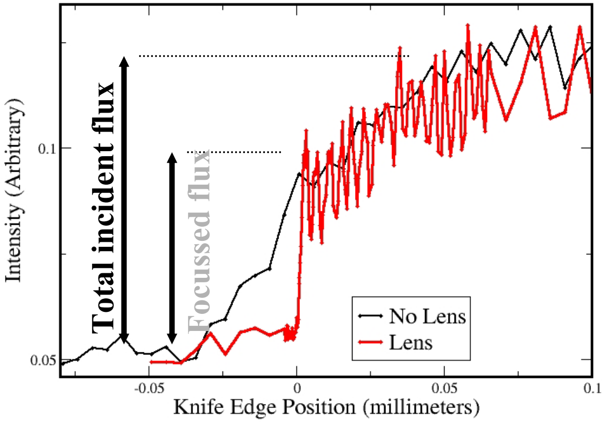
K.Evans-Lutterodt, J.Ablett, A.Stein

- Our groups current results
- Brief review of Refractive optics and its limits
- Motivation for kinoforms
- Features/trade-offs of kinoforms
- Are there fundamental limits for these optics?

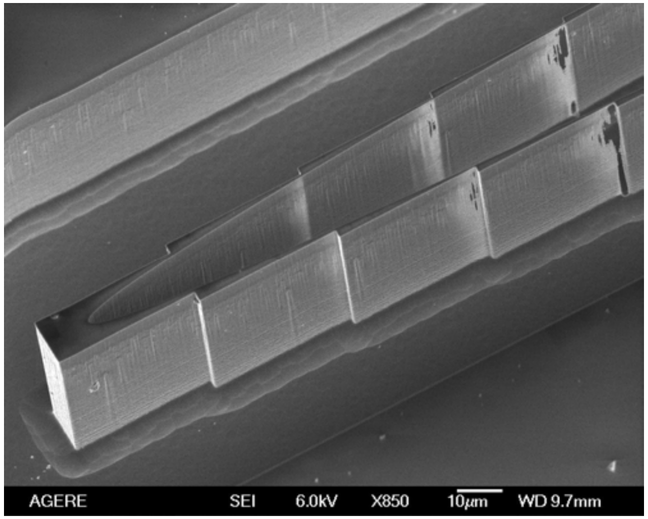
*K. Evans-Lutterodt et al., “Single-element elliptical hard x-ray micro-optics”, Optics Express 11 (8) 919-926, 21 April 2003.

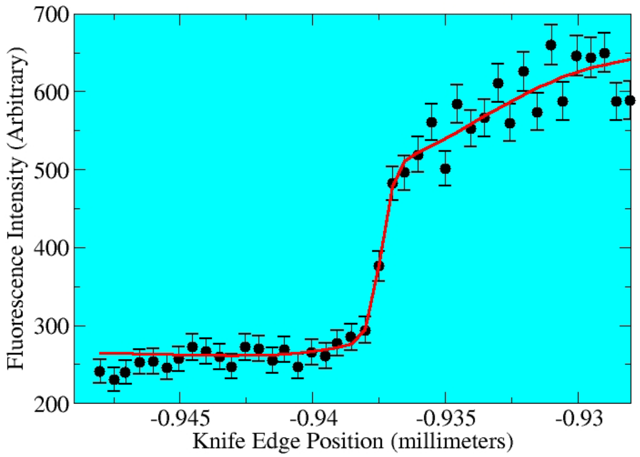
Status: Local NSLS results

Submicron performance with 100micron Aperture

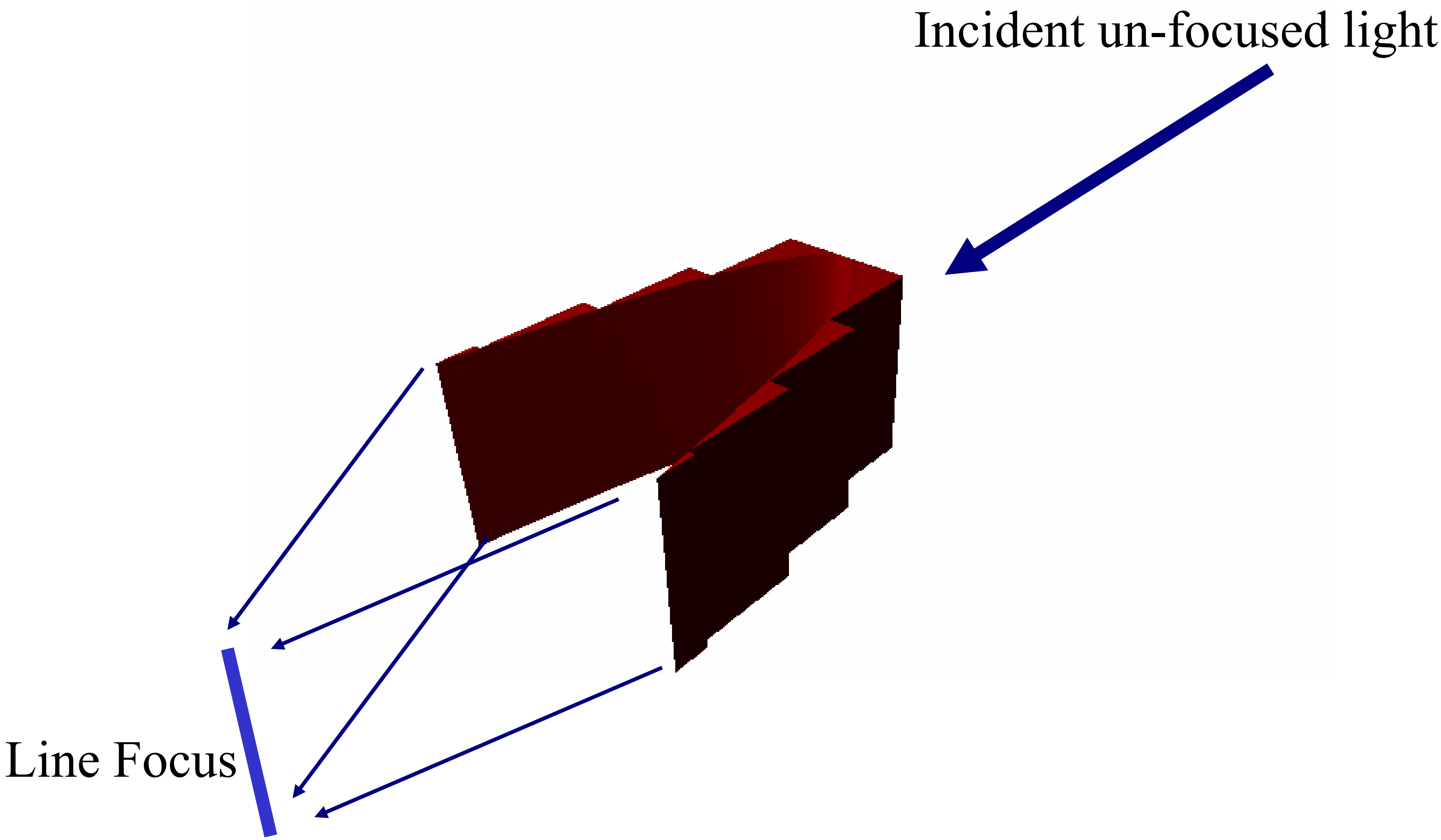


•Knife edge consists of Cu metal grating with 2 micron period.
•Figure on left shows a knife edge scan with and without a lens in the path.
•Efficiency is greater than 60%



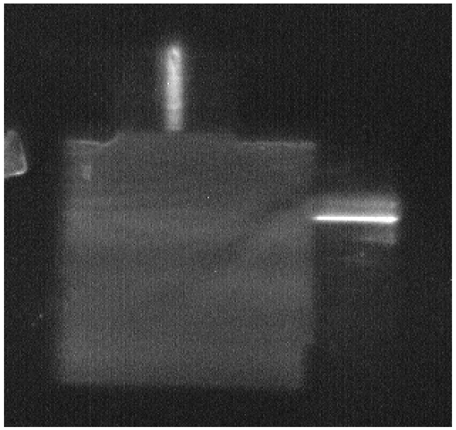


Detailed knife edge scan showing submicron performance. Distance between experimental points is 0.5 micron

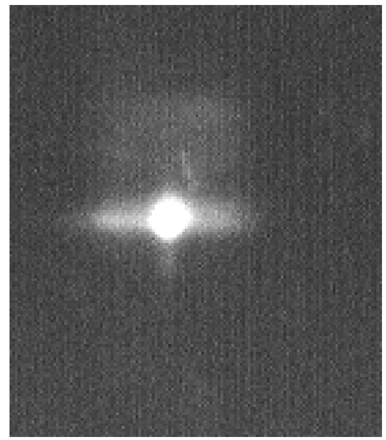

Incident un-focused light
Line Focus

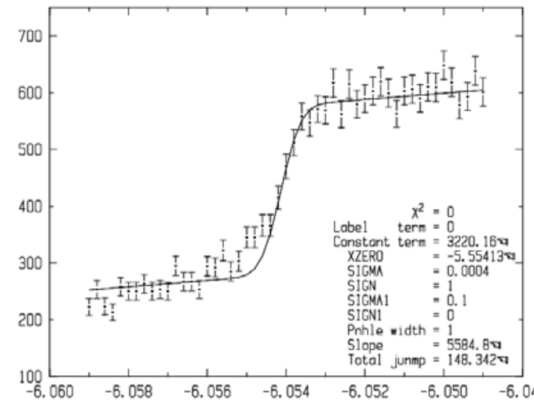
Status: Local NSLS results
A 4 micron by 0.6 micron spot from a crossed lens

Horizontal lens

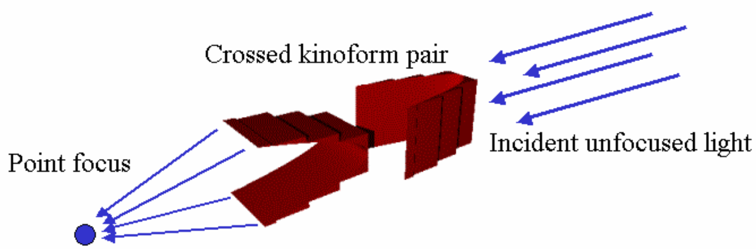


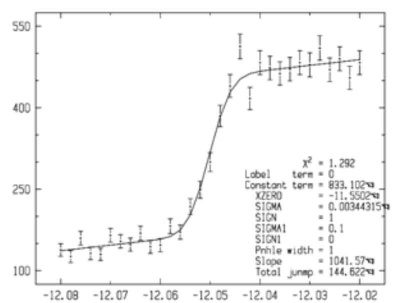
Vertical lens





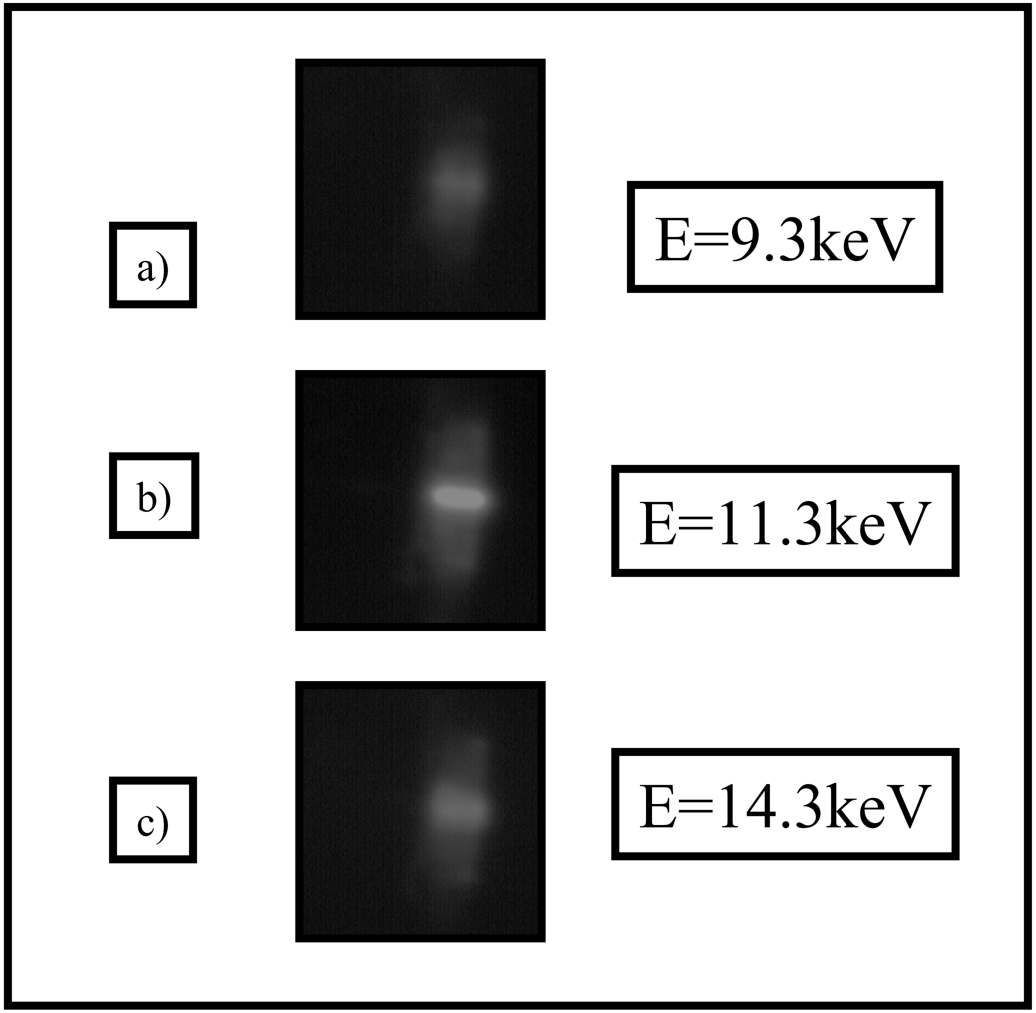
Vertical knife edge 0.6 microns





Horizontal knife edge; 4 microns

CCD images of a focused spot at different Energies, as imaged by a YAG:Ce crystal. The design energy is 11.3keV, and the spot is its sharpest. As one goes up in energy (14.3keV) and down in energy (9.3keV) the peak broadens.



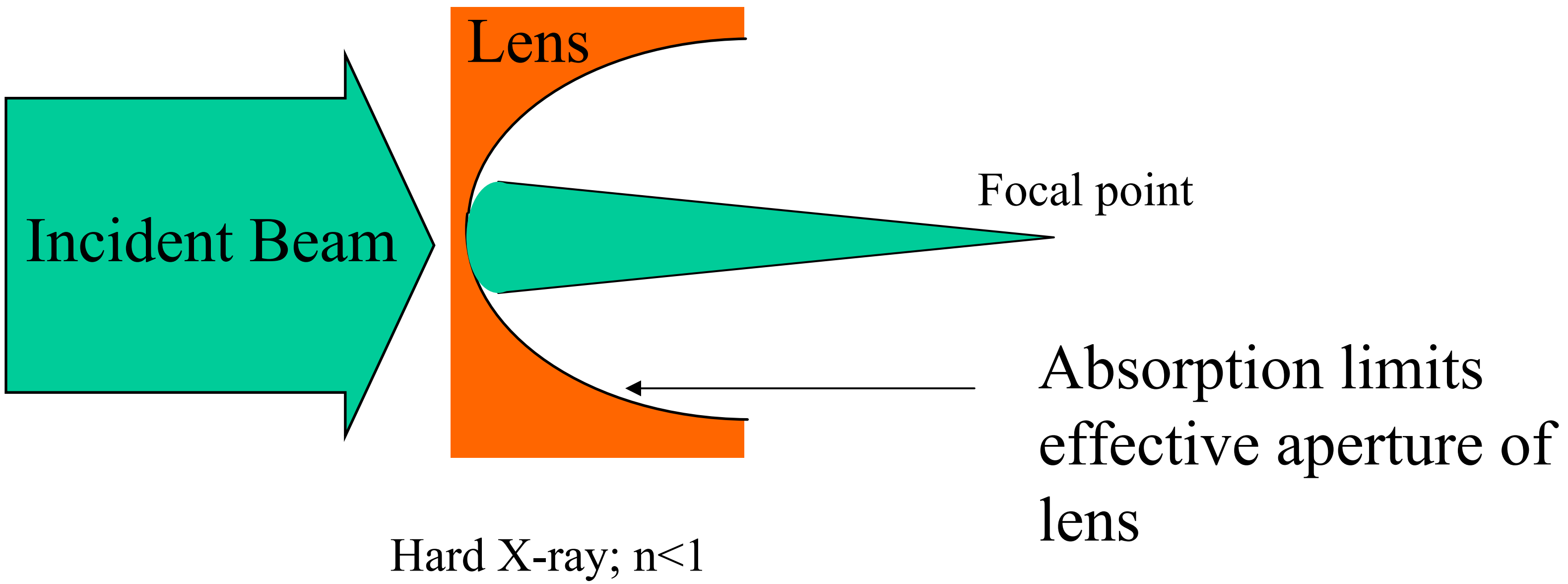
- A kinoform is a phase optic
- Assymetric computer generated profile
- Efficiency and resolution are metrics to consider
- Phase profile accuracy is important;
  => Elliptical shape for point to parallel refractive optic.

For far field optics, resolution is λ/(Numerical Aperture)
Limiting value of N.A. is 1

“State of the Art* ” of the different microscopies			
Method	Wavelength	Resolution	Ratio
Optical	200nm	200nm	1
Electrons	0.05nm	0.1nm	2
Soft X-rays	10nm	30nm	3
Hard X-rays	0.1nm	200nm	2000 (We need better optics)

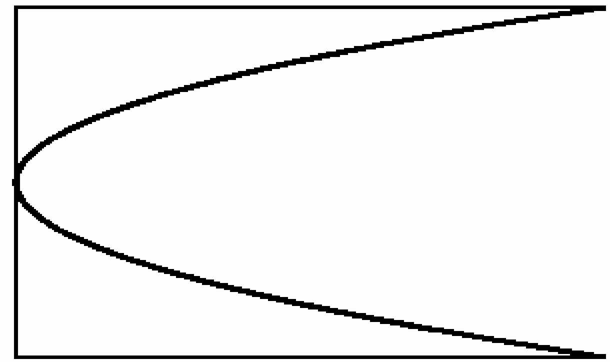
*Very crude

For most refractive optics, absorption limits aperture, and hence resolution

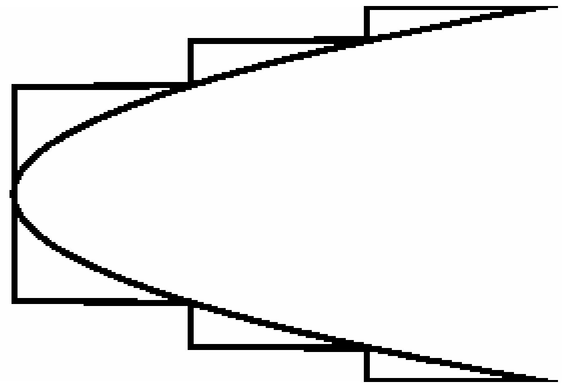


Is there a way around this?

Instead of solid refractive optic:



Use a kinoform:



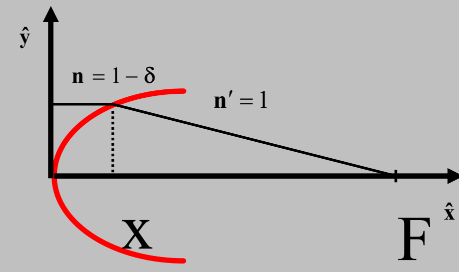
Deleted sections reduce loss but constrain the bandwidth of optic
(There is no free lunch!)

What is the best shape for the lens?

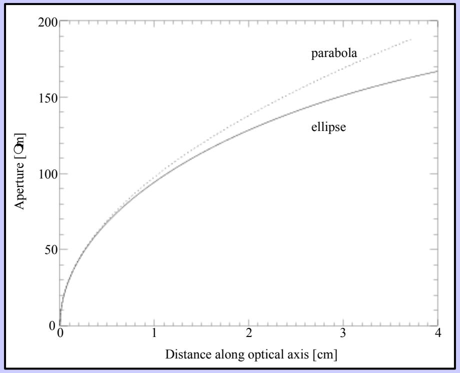
From Fermats theorem for n<1 the best shape for a point to parallel converter is an ellipse.

$$nx + n'\sqrt{(F-x)^2 + y^2} = n'F$$

$$y^2 + (2\delta - \delta^2)x^2 - 2\delta F x = 0$$

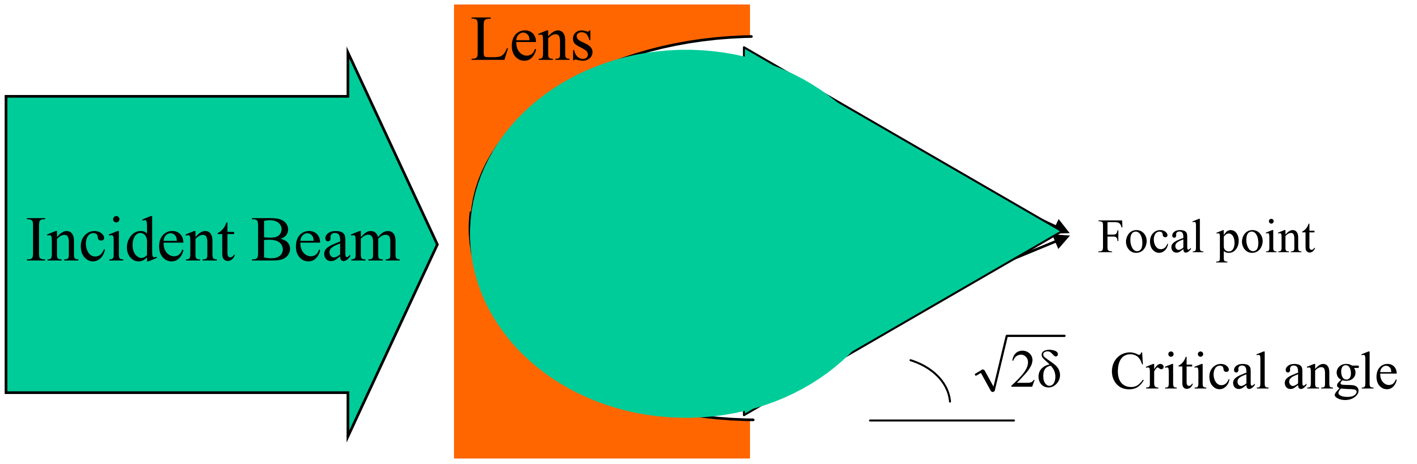


Clearly, the ellipse and parabola are similar near the optical axis



Hecht

Even for no loss there is still a limit; for a single lens it is the critical angle



Resolution $= \dfrac{\lambda}{N.A.} = \dfrac{\lambda}{\left(\dfrac{Aperture}{focal\_length}\right)} = \dfrac{\lambda}{\left(\dfrac{focal\_length * \theta_c}{focal\_length}\right)} \approx \dfrac{\lambda}{\sqrt{2\delta}} \approx 100nm$

The resolution of a single low loss lens, is limited by critical angle

This observation is a central issue in a "controversy".

It should not be a controversy, because there is a way around this; use compound kinoform lens

*K. Evans-Lutterodt et al., “Single-element elliptical hard x-ray micro-optics”, Optics Express 11 (8) 919-926, 21 April 2003.

…..One implication of the elliptical shape is that for a given focal length and refractive index, the diffraction-limited resolution given by the Rayleigh criterion

$$f\lambda/(\text{aperture})=f\lambda/2b \sim \lambda/\sqrt{2\delta}$$

is dependent only on the choice of material and the wavelength, even for lossless material and in the refractive limit. For $\delta = 10^{-6}$, one gets a resolution of $\sim 10^{3}\lambda$. This is not a fundamental limit; by using more than one element i.e. a compound lens, one can exceed this limit.

….

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Focusing X-Ray Beams to Nanometer Dimensions

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We address the question: what is the smallest spot size to which an x-ray beam can be focused? We show that confinement of the beam within a narrowly tapered waveguide leads to a theoretical minimum beam size of the order of 10 nm (FWHM), the exact value depending only on the electron density of the confining material. This limit appears to apply to all x-ray focusing devices. Mode mixing and interference can help to achieve this spot size without the need for ultrasmall apertures.

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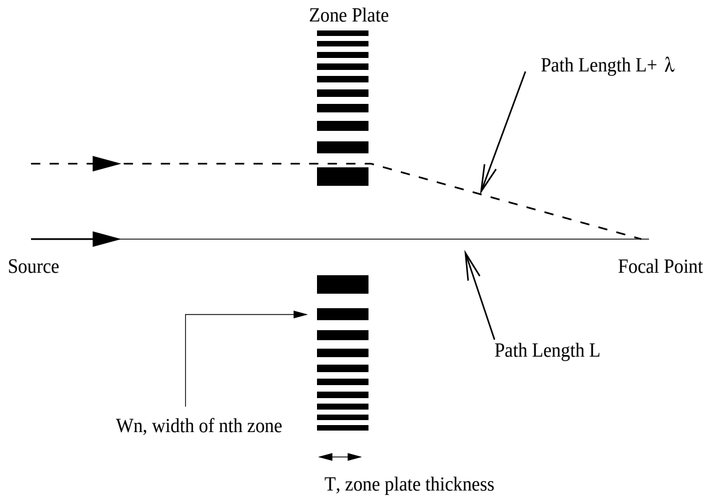
A very brief review of Zone Plates



Equation for fresnel boundaries

$$y_m = \sqrt{(2mf\lambda + m^2\lambda^2}$$

Table 2.1

Type of zone plate	I_1/I_0, %	I_2/I_0, I_3/I_0, ..., %	Undiffracted portion, %	Absorption, %
Fresnel (amplitude)	10.1	0, 1.1, 0, 0.4, ...	25	50
Rayleigh–Wood (phase)	40.4	0, 4.5, 0, 1.6, ...	0	0
Gabor (amplitude)	6.25	0	25	68.75
Gabor (phase)	34	10, 1, 0.1, 0.06, ...	0	0
Kinoform (phase)	100	0	0	0

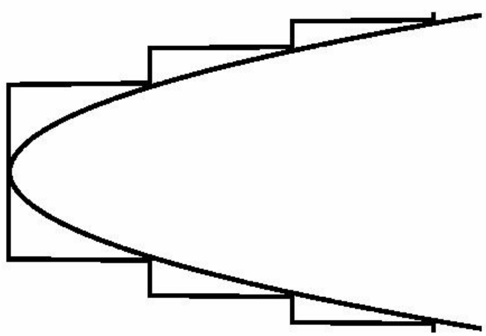
(Aristov)

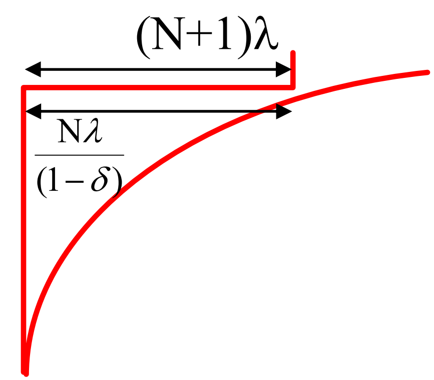
Fresnel lens (kinoform) ; main point

- If you are willing to work at a fixed wavelength, you can reduce loss.

- Remove sections such that at a fixed wavelength the phase shifts by multiples of 2π. Original Fresnel lighthouse lens had large phase shifts (>> 2π). Kinoform is coherent limit of Fresnel lens.

- Steps are $\frac{\lambda}{\delta}$ thick corresponding to 2π phase shift, or multiples





Spot size of order smallest feature

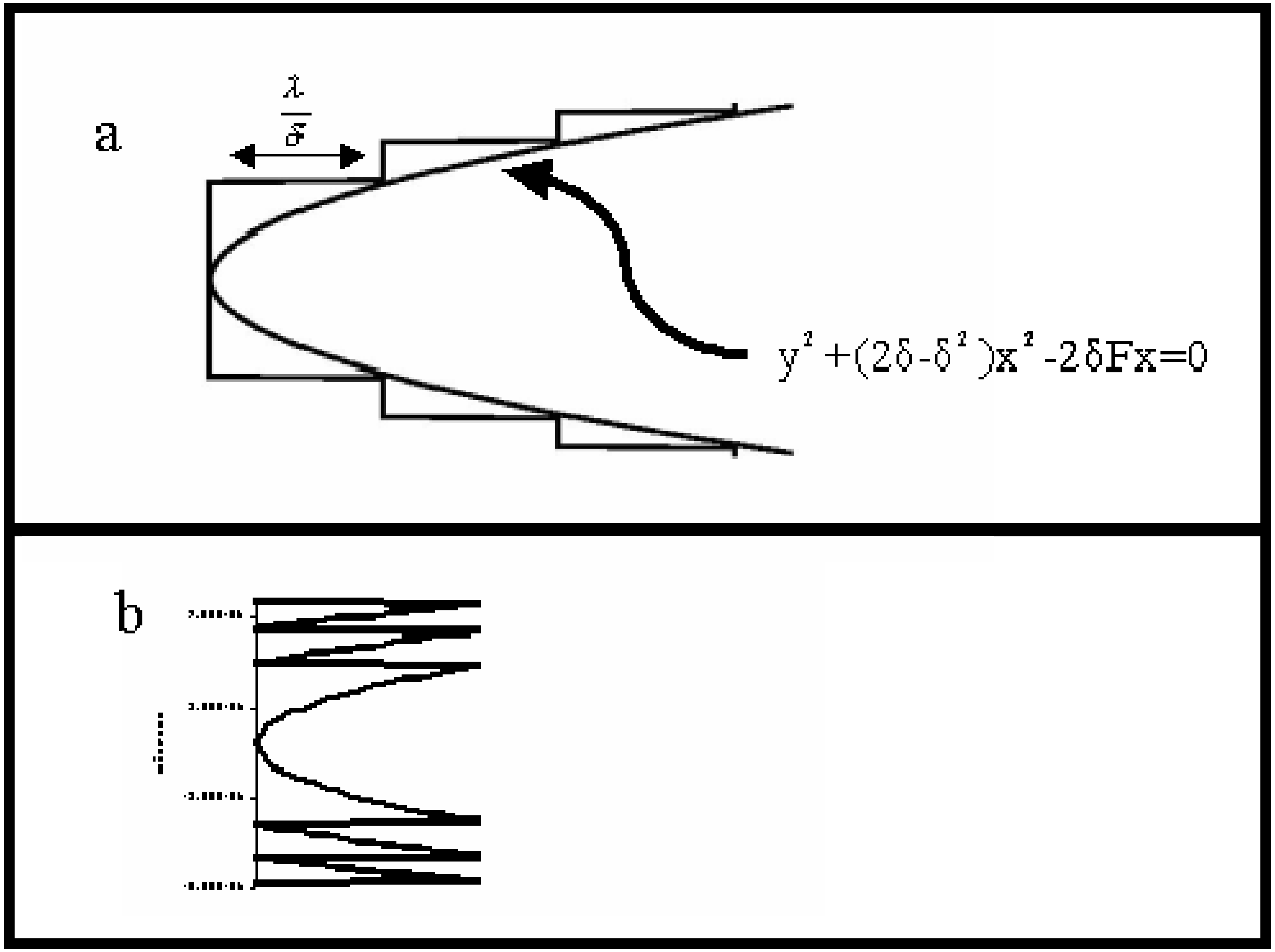


Figure 2a) Figure showing the elliptical profile of "long" kinoform lens, and the sections removed to reduce loss. A parallel beam comes from the left and the focused spot is on the right.
Figure 2b) A "short" kinoform lens, where the segments are folded into one plane; this is the more

Is it diffractive or refractive?

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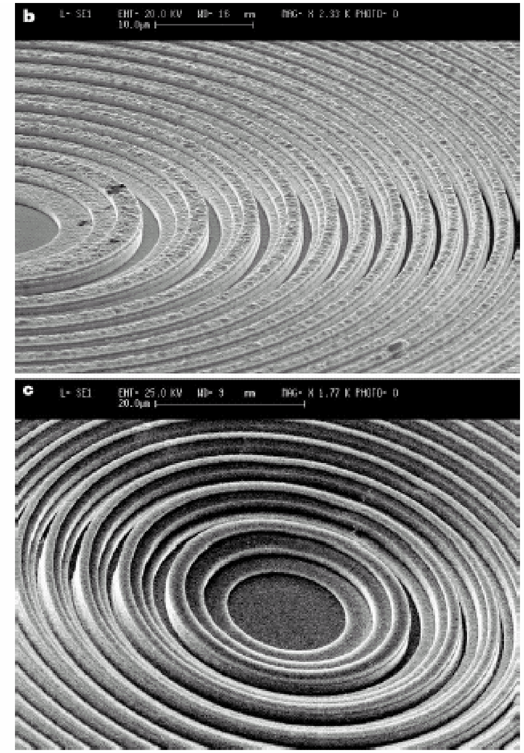
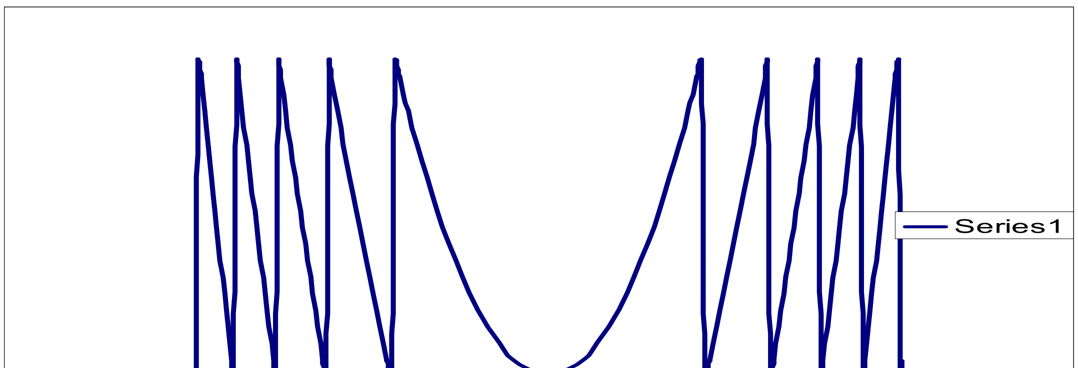
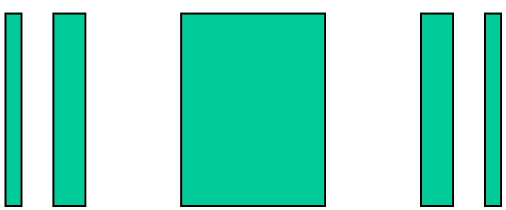




Kinoform



Binary zone plate

Magnitude of Phase jump is a "refractive/diffractive" knob

Features:

The Fresnel lens has a loss that is almost independent of aperture.

•Transmission $$T = e^{-(2\pi\frac{\beta}{\delta})}$$

•Implies lens resolution is no longer limited by loss
⇒Back to elliptical shape limit

▪There is a minimum loss; you need at least enough thickness to give 2π phase shift.

▪For Beryllium at 10keV $\delta \approx 3.1 \times 10^{-6}$, and $\beta \approx 7.5 \times 10^{-10}$, and so the transmission T of a single Beryllium Fresnel lens $T \approx 0.9985$

▪Zone plate maximum is 40% for phase

Features:

High heat load capacity (2 for 1)

- In the best case, the optic is designed not to absorb much heat. Should have a high heat load capability.
- Complicated to calculate
- First pointed out by Lengeler,Snigirev.

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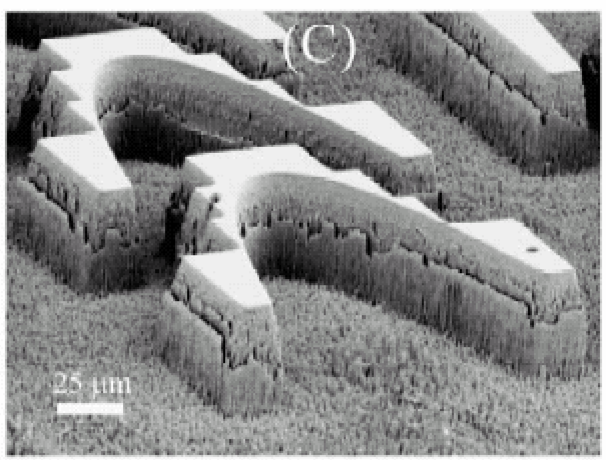
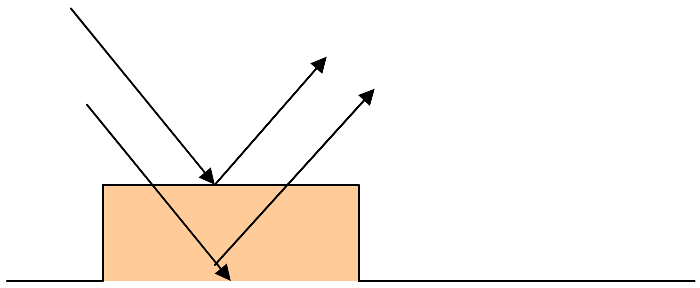


Etching Diamond for high heat loads!

Features:

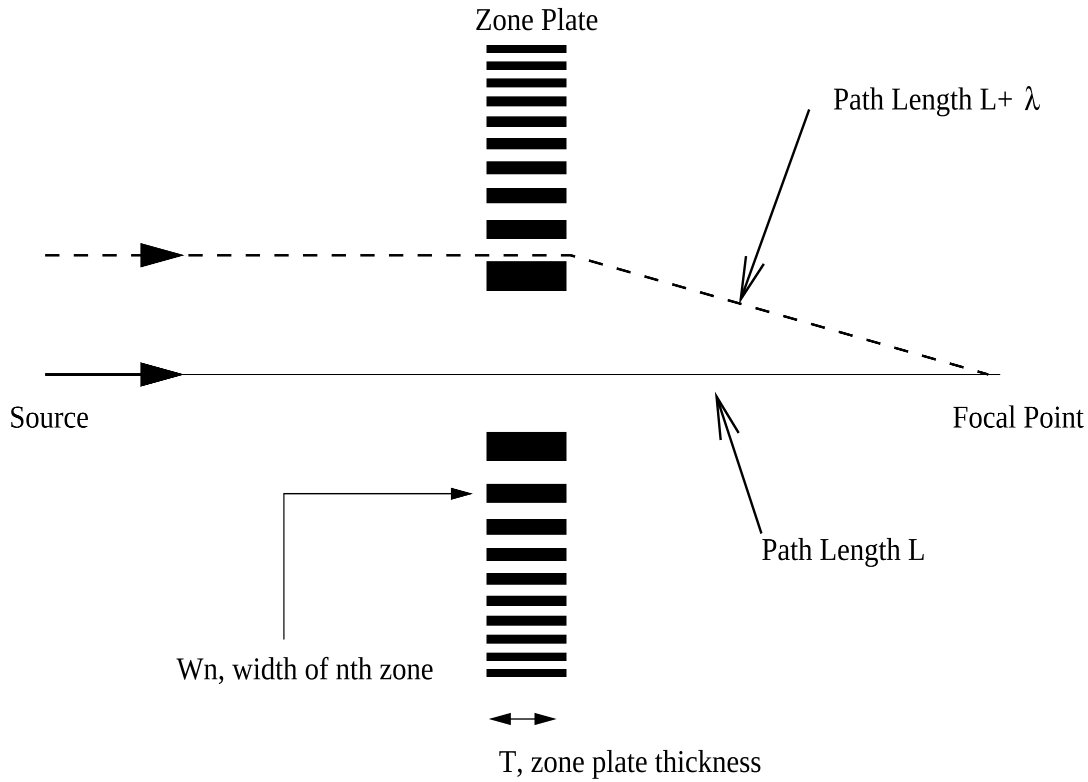
Favourable phase error comparison with mirrors.

- Consider a mirror with a bump on it
- The path length difference caused by bump is 2dsinθ
- To get a 0.5π phase shift bump must be $0.25(\lambda/\sqrt{\delta}) \approx 25$nm



- Consider a refractive lens
- To get a 0.5π phase shift bump must be $0.5(\lambda/\delta) \approx 15$microns
- The precision of an e-beam writer is ≈ 1nm (*). Possible errors very small

Potential road block for zone plate



- The spot size is of order the smallest zone

  Work at harmonics, reduces efficiency
- As photon energy increases, the zone plate thickness T increases

To get smallest spot sizes at hard x-ray energies requires
=> Large aspect ratios that are difficult to manufacture

Features: Going beyond the manufacturing tolerance

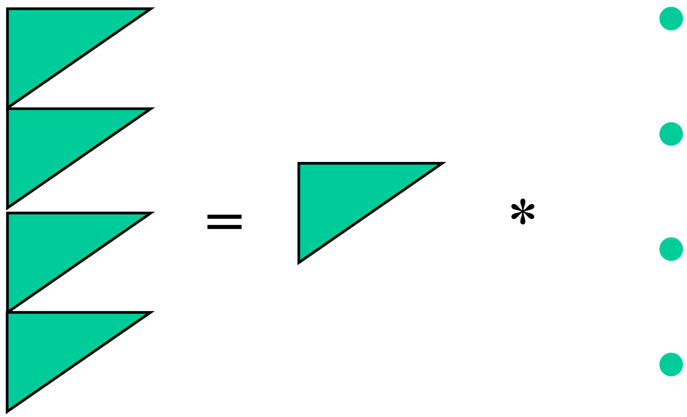
As in the zone plate, the smallest feature is proportional to the focus spot. Does this limit the spot size?

Answer: Instead of 2π phase shifts, use 4π, or more. The features get bigger and easier to manufacture. We already do this. The limit here is the loss. Under investigation.

Note: this is analogous to using f/3 for higher resolution in the normal binary zone plate. Does not seem to be an efficiency penalty.

By the way there is a small factor of 2 improvement in resolution relative to binary zone plate.

Intuition for the kinoform from the simpler Fresnel prism

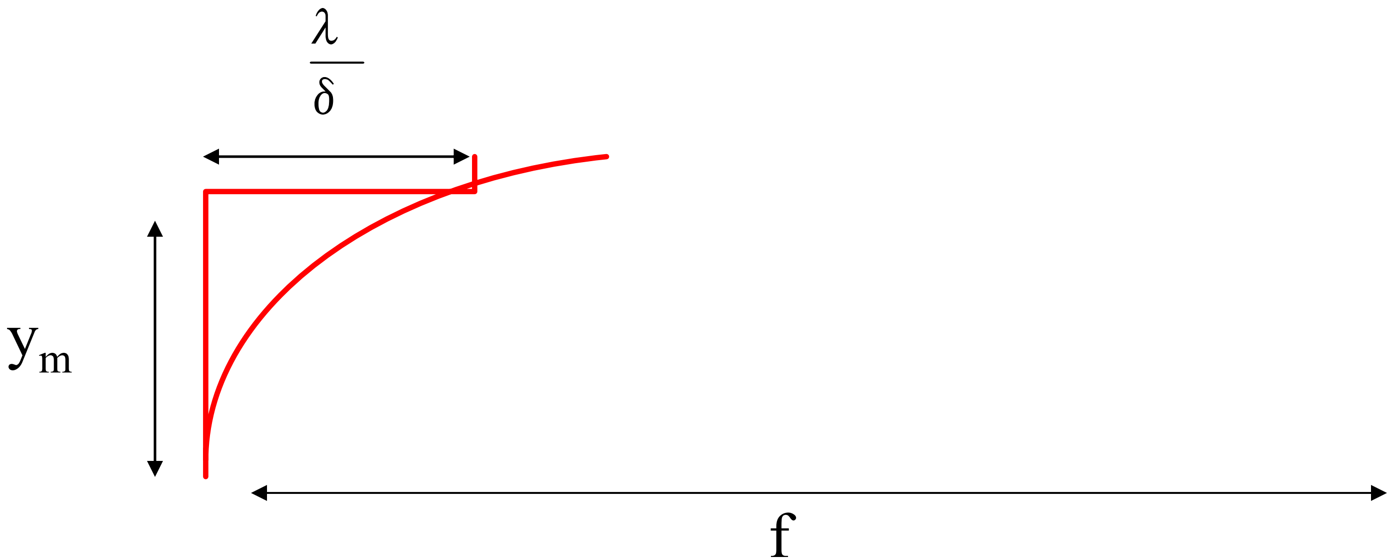


$$\rho(\mathbf{r}) = \mathbf{prism(x)} * \sum_{\mathbf{m}} \delta(\mathbf{x} - \mathbf{ma})$$

$$\rho(\mathbf{k}) = \mathbf{prism(k)} \times \sum_{\mathbf{n}} \delta(\mathbf{k} - \mathbf{n}(\frac{2\pi}{\mathbf{a}}))$$

Another connection between the zone plate and kinoform

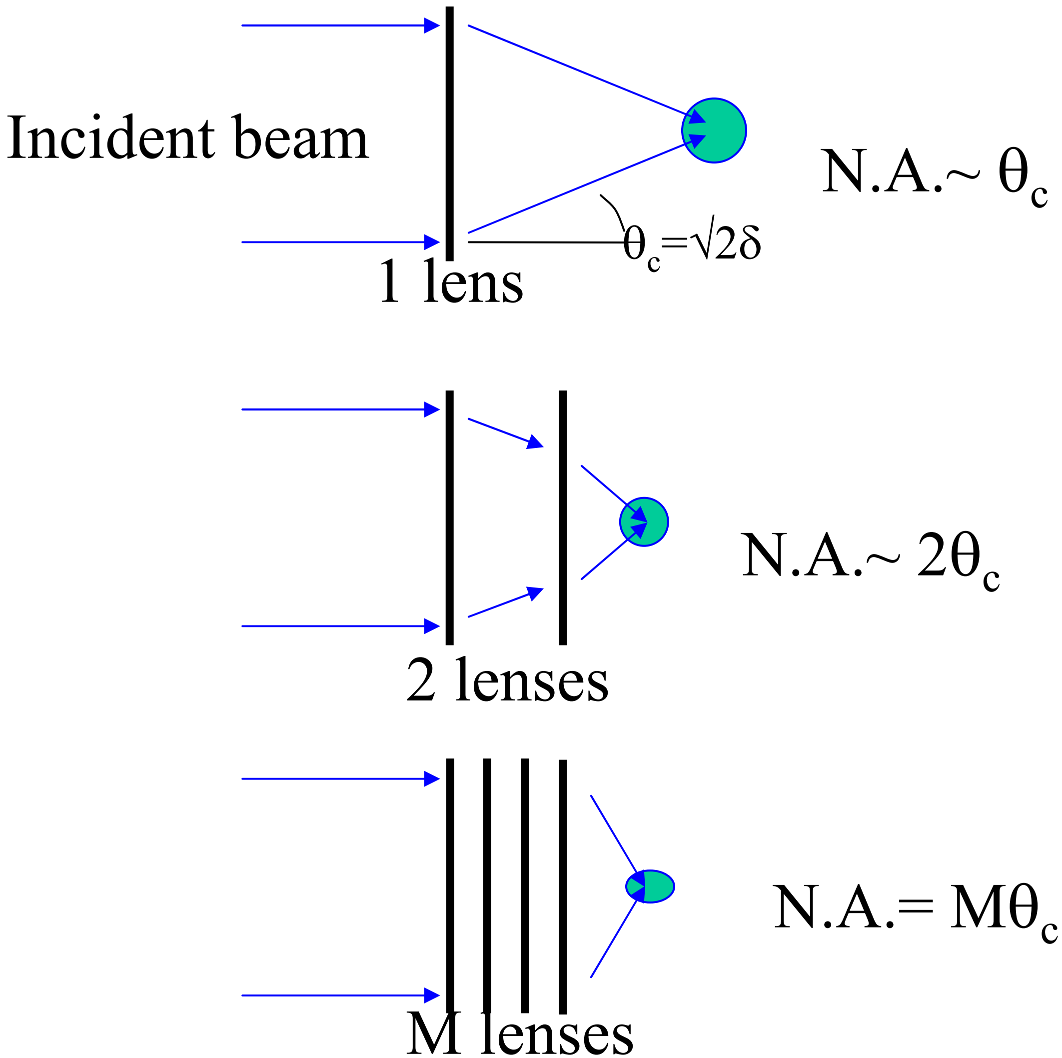
Zone plate boundaries $y_m = \sqrt{(2mf\lambda + m^2\lambda^2}$



Kinoform boundaries: $y_1 = \sqrt{(2f\lambda + \lambda^2(1-(\frac{2}{\delta}))}$

Very similar but not identical. What is the connection?

How compound kinoform lenses can improve resolution



Since resolution is λ/(N.A.), M lenses will have λ/(M*(N.A.))
Remember that each lens introduces some loss.

Optimize Gain

- Each lens gives some loss
- Each lens increases gain (flux into spot)
- $I \propto N x^{N}$
- N is the number of lenses, x is the loss of a lens
- Note: you do not have to optimize gain; you can choose to get a smaller spot, and increase the background.

A conservative, lens calculation for NSLS2

•We consider a compound lens fabricated out of a stack of Fresnel lenses. For Beryllium at 10keV $\delta \approx 3.1 \times 10^{-6}$, and $\beta \approx 7.5 \times 10^{-10}$, and so the transmission T of a single Beryllium Fresnel lens $T \approx 0.9985$. For 200 lenses, corresponding to 100 lenses for each axis, the total transmission is 75% of the incident light.

• For the paraxial limit we make the standard approximation that the focal length of the stack is (f_0/N) where f_0 is the focal length of an individual lens and N is the number of lenses. If we conservatively stay within the paraxial limit, we estimate a focal length of $f_0 \approx 2.2y/\sqrt{\delta}$ where y is the required aperture and δ is the refractive index.

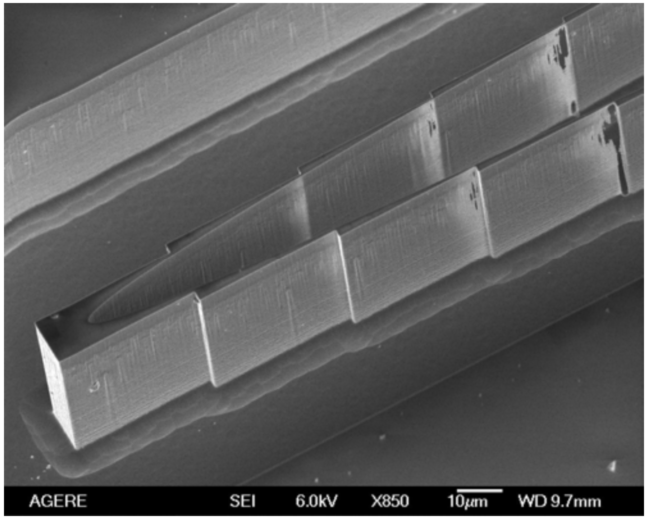
•The desired aperture y is of order 5x10-4 m, (≈ 3 x (distance from source) x $\sigma_y' = 3 \times 40\text{m} \times 4 \times 10^{-6}$).

•The estimated f_0 is 0.64 m (one lens).

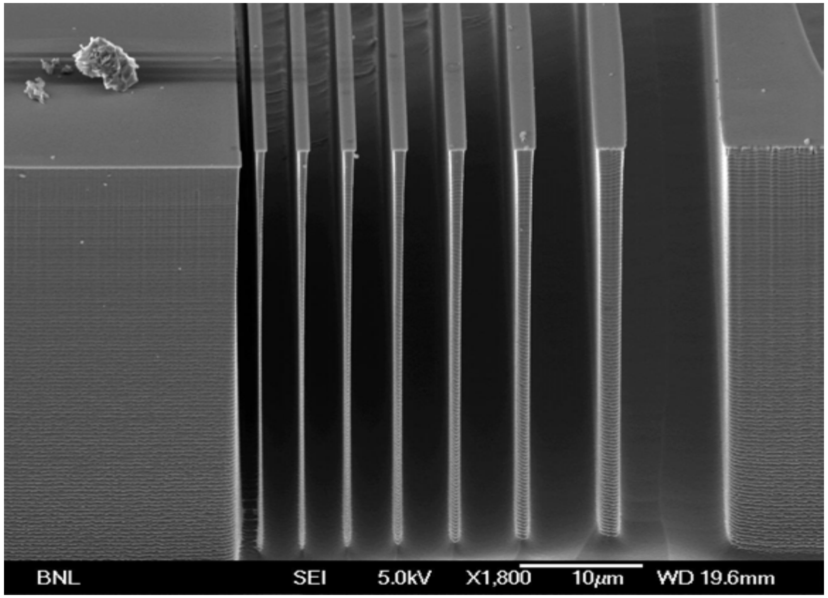
•The net focal length for 100 lenses is 6.5mm, and the resulting resolution is λ/(Numerical Aperture) is 1.6nm.

Summary

•If you are willing to accept the fixed wavelength limitation, kinoform lenses have some useful features.
•For some applications the bandwidth issues are not a problem
•Clearly they work, and are improving.



What is to be done?



1. Improve depth and fidelity of etch, currently 80microns deep

2. Figure out how to create cylindrically symmetric self-supporting structures (Complicated micro-fabrication, not planar)

3. Figure out how to use materials other than Silicon