

## Beamlines: Secondary optics (Part 1)

Synchrotrons and x-ray  
free-electron lasers  
Techniques and  
applications

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Video



# Contents and objectives of this video



- Need for secondary/microoptics
- Compound refractive lenses

Welcome back. We're now beginning week six, the final week of this first of two sister courses, synchrotrons and X-ray free-electron lasers, techniques and applications. This week, we finished discussing beam lines and instrumentation by first reviewing secondary optics components, specifically micron and sub-micron focusing devices, and second, looking at different types of photon and electron detectors. In this video, we review the first of three types of microfocused devices, the so called compound refractive lens, or CRL.

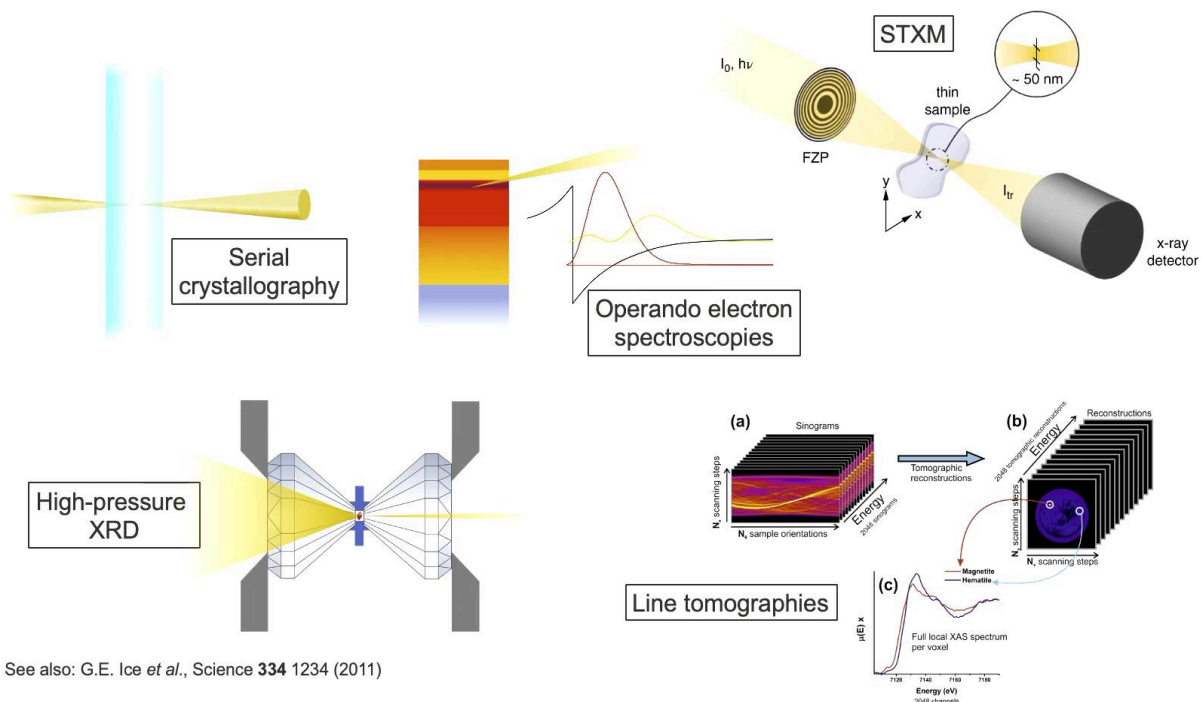
Notes

Summary



0m 04s

# Applications of micron and submicron focussing



Before looking at CRLs in detail, we should first consider what reasons there might be for using secondary optics. X-ray microprobes are nowadays a standard tool in synchrotron science with applications in crystallography, scanning based imaging such as scanning transmission X-ray microscopy, and line tomographies, high pressure sciences and operando, and in situ studies of micro electronic devices and natural complex systems, to name just a few examples. The advent of DLSRs with the much improved emittance promises similar gains in focusing capabilities.

Notes

Summary



0m 46s

# Need for secondary optics



- Source size @ undulators
  - 3<sup>rd</sup> gen.  $\sim 200 \times 5 \mu\text{m}^2$
  - DLSRs  $\sim 10 \times 5 \mu\text{m}^2$
- Focus on sample  $< 1 \mu\text{m}$ ?
  - Demagnify by factor  $\gtrsim 20$
  - Impractical for most mirrors
    - $f \sim 1 \text{ m}$
    - Bending radius  $\lesssim 500 \text{ m}$
- Vibrations from upstream components

Even for the newest generation of synchrotrons, the source size might be typically of the order of 10 by five square microns. In order to obtain a focus of less than a micron, demagnification factors exceeding approximately 20 are therefore required. Now, this is impractical for mirrors that are flexed to provide a dynamical focal spot size due to the relatively short bending radius that would be required. Although fixed radius mirrors that have been ground for a certain focal length can be used down to focal spot sizes of the order of a micron, much smaller spot sizes are excluded, as the physical size of the mirror in the beam propagation direction limits the minimum mirror to sample distance. Now, another perennial problem is that of vibrations. The electron beam itself can drift or vibrate, while the X-ray beam can vibrate due to upstream components vibrating themselves due to many possible reasons, such as water cooling of components such as mirrors or monochromators. So even if the beam might have an instantaneous focus of the required size, if the position of this focus vibrates sideways, the effective focal spot size will be concomitantly higher.

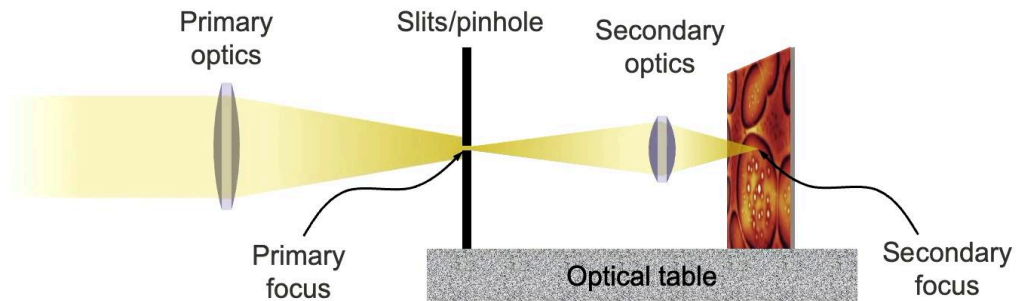
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Summary



1m 32s

# Generic setup for secondary optics



A typical setup for secondary optics might look something like this. A set of slits or a pinhole is placed close to the focal plane of the primary optics on an optical table or massive body that vibrates to an extent significantly less than that of the desired focal spot size of the secondary optics. This might be achieved passively simply by inertia of the optical table, or there may be some active feedback using, for example, piezo elements to compensate for residual vibrations. The secondary optics are typically compact, allowing lens to sample distances as small as a few millimetres. Clearly, the sample needs also to be mounted so that it remains sufficiently still or moves in a quasi, vibrationless, controlled manner, such as in scanning experiments.

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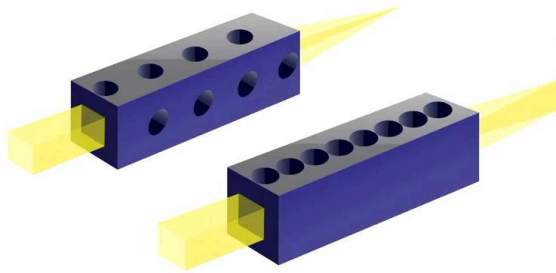
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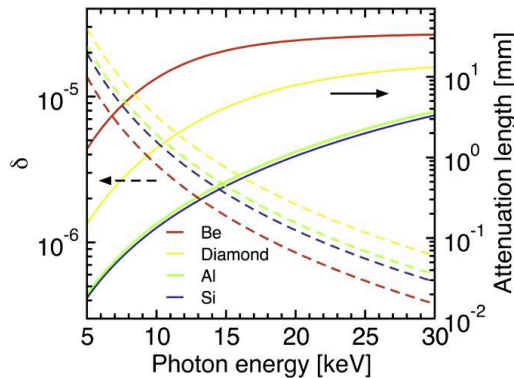
3m 05s



# Compound refractive lenses



- “Opposite” of conventional lenses in visible
- Light, weakly absorbing material
- Stackable
- “Simple” circular cross-sections  
⇒ significant aberrations
- Highly chromatic



$$f = R/2n_h\delta$$

$$\delta = \frac{\rho r_0}{2\pi} \lambda^2$$

$$f \propto 1/\lambda^2 \text{ or } (h\nu)^2$$

The first type of micro focusing element we will discuss is the compound refractive lens or CRL. CRLs, in their simplest form, consist of holes drilled out of X-ray transparent material such as beryllium for example. The focal length is given by the hole radius big R divided by two times the number of holes and h, and their refractive index decrement Delta. Now, this last parameter is equal to about two times 10 to the minus six for beryllium at 12 keV. Hence, a CRL consisting of an array of 3,200 micron diameter holes has a focal length of approximately 70 centimetres. CRLs have the advantage that they are easy to align in the X-ray beam. They do not alter the beam axis, and the elements can be stacked after one another to change the focal length. Their main disadvantages are A, that the focal length is proportional to the square of the X-ray photon energy, which means that they must be positioned, restacked, or replaced if the photon energy has changed, and B, that the transmission is in general fairly poor. A 100 hole CRL made of beryllium with walls of 100 micron thickness separating adjacent holes has a transmission of 0.5 at 12 keV.

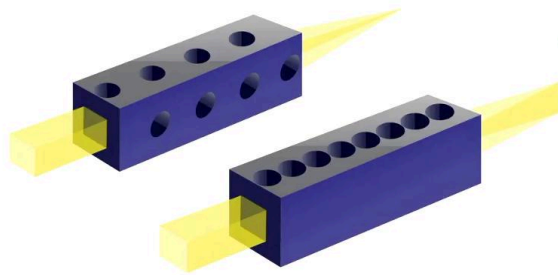
Notes

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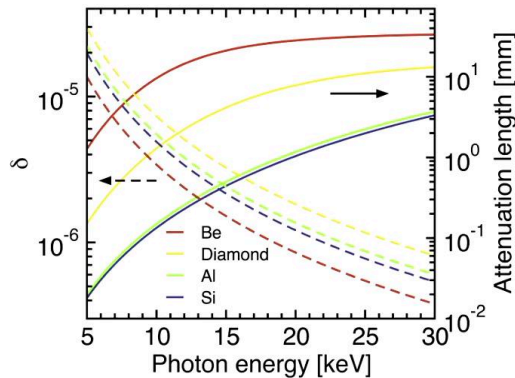


4m 05s

# Compound refractive lenses



- “Opposite” of conventional lenses in visible
- Light, weakly absorbing material
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$$f = R/2n_h\delta$$

$$\delta = \frac{\rho r_0}{2\pi} \lambda^2$$

$$f \propto 1/\lambda^2 \text{ or } (h\nu)^2$$

Moreover, because refraction of X-rays is so weak, the hole diameter  $R$  needs to be quite small in order to achieve a reasonably short focal length. But this can often mean that the beam propagates through the sides of the holes where the deviations from a parabola are large, resulting in significant optical aberrations. The choice of material depends on the photon energy range for which the CRL is being manufactured, the required focal length and the acceptable loss in flux due to absorption. So for example, although the attenuation length of diamond at, for example, 15 keV is at approximately five millimetres, five times smaller than for beryllium, its refractive index decrement is more than double that of beryllium.

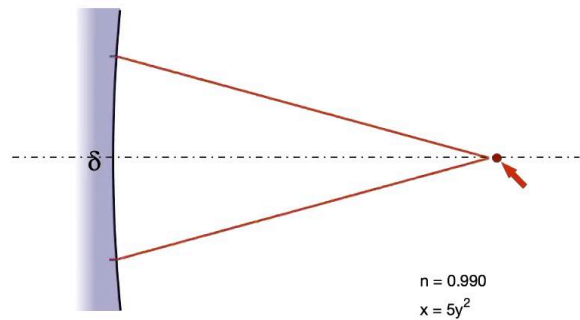
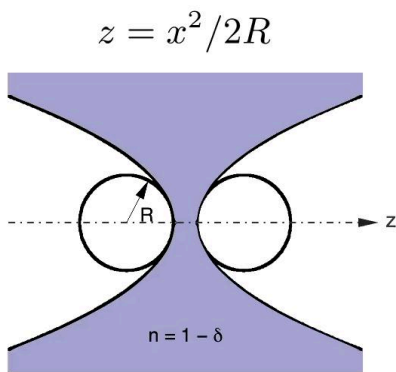
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5m 47s

# Parabolic compound refractive lenses



- Approximately  $f = R/\delta$  (single plano-parabolic lens)
- Assumes  $R \ll f$

Much effort has been made in recent years to fabricate CRLs with true parabolic surfaces using sophisticated mechanical milling or even focused ion beam milling. The equation describing the profile of a parabolic CRL is  $z$  is equal to  $x$  squared divided by  $2R$ , whereby  $z$  is the direction of propagation,  $x$  is perpendicular to  $z$  and has its origin on the CRL surface, and  $R$  is the radius of a circle that best approximates the parabolic surface close to the central axis. Note by the way, that the focus is slightly dependent on the position of the parallel X-rays and where they pass through the parabolic CRL relative to the central axis, though this effect is very small for  $R$  much smaller than the focal length  $f$ .

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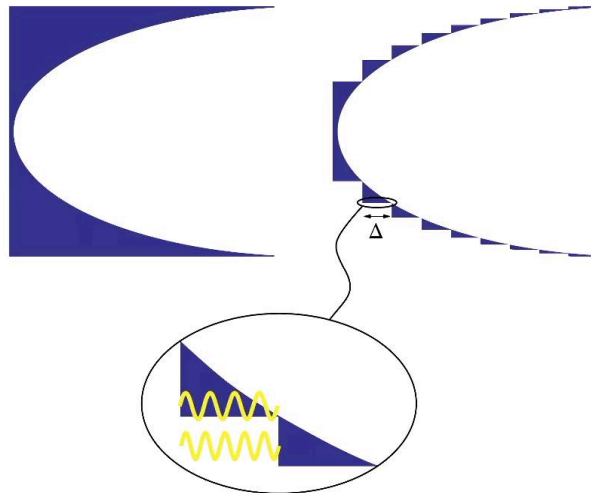




# Parabolic kinoform CRLs



Point Arena Lighthouse, California  
1<sup>st</sup> order Fresnel lens



$$\Delta = m\lambda/\delta$$

$$\text{e.g. } \Delta = 1 \times 10^{-10} \text{ m} / 5 \times 10^{-6} \\ = 2 \times 10^{-5} \text{ m} = 20 \mu\text{m}$$

Parabolic CRL can be concatenated to make them more compact. The principle of these so called kinoform lenses is similar, if not identical to the approach used in refractive Fresnel lenses, such as seen here in large format of the lens formerly used at the Point Area Lighthouse on the coast of California. Consider first a standard plain old concave CRL. We now remove blocks of thickness Delta from the CRL material. Delta is chosen so that the radiation travelling just outside the cutaway executes one more cycle than the neighbouring radiation just inside the material, which has a longer wavelength, on account of the material having a refractive index less than unity. The two rays are therefore in phase at the beginning of Delta, and again in phase at the end of Delta. This condition is satisfied when big Delta, is equal to m Lambda divided by small Delta, whereby the integer m allows for differences in the optical path of integer multiples of the wavelength Lambda. If we insert typical values for Lambda equals one Angstrom, Delta equals five times 10 to the minus six, and m equals one, we obtain cutaway depths of 20 microns. Note that Big Delta is inversely proportional to Lambda, as small Delta is proportional to Lambda squared.

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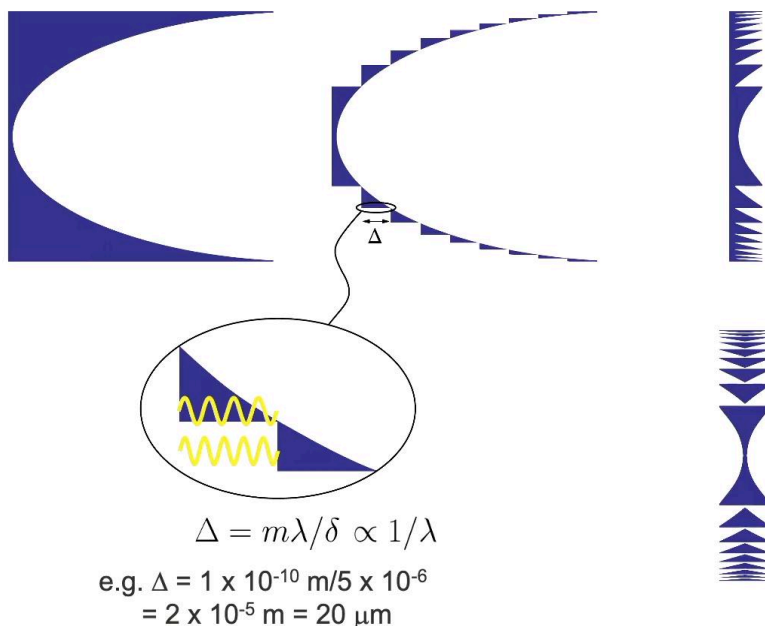


7m 40s

# Parabolic kinoform CRLs



Point Arena Lighthouse, California  
1<sup>st</sup> order Fresnel lens



Next, one can take each individual concentric portion of the CRL and concertina them to a common plane. This not only makes the CRL more compact, but also easier to fabricate by milling techniques or other approaches. And moreover, reduces the absorption of the CRL. Lastly, in special cases, it might be possible to mirror this profile on the back side of the CRL, thus doubling its focusing power.

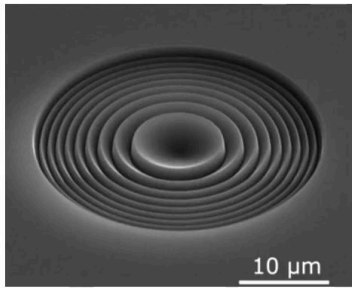
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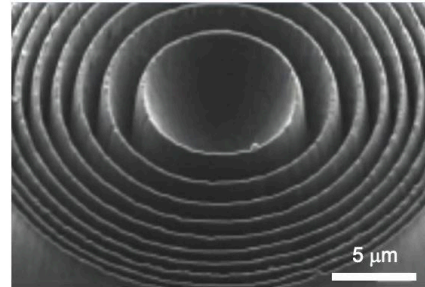
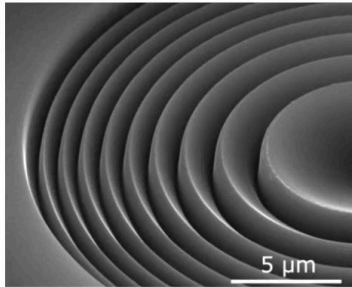
9m 19s

# Parabolic kinoform CRLs – examples



Ion beam  
milling in silicon

K. Keskinbora *et al.*,  
Adv. Opt. Mater. **3** 792 (2015)



3D nanoprinting of plastic  
on Si<sub>3</sub>N<sub>4</sub> membrane

U. Sanli, H. Ceylan, *et al.*,  
Adv. Mater. **30** 1802503 (2018)

Images of real kinoform lenses are shown here. On the left, the lens was fabricated via ion beam milling of silicon wafers. The right hand image shows a kinoform CRL made by 3D nanoprinting of amorphous plastic on ultrathin silicon nitride membranes, a cheap and effective alternative that has only recently become possible with advances in 3D printing technologies.

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9m 54s

## In the next video...



In the next video, we look at micro focus lenses based on diffraction, namely Fresnel zone plates. Although relatively inefficient due to absorption effects and unavoidable higher order modes, these devices are extremely popular for those who really want to push the envelope and obtain focal spot sizes of around 100 nanometres or even smaller without investing huge sums of money.

Notes

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10m 23s