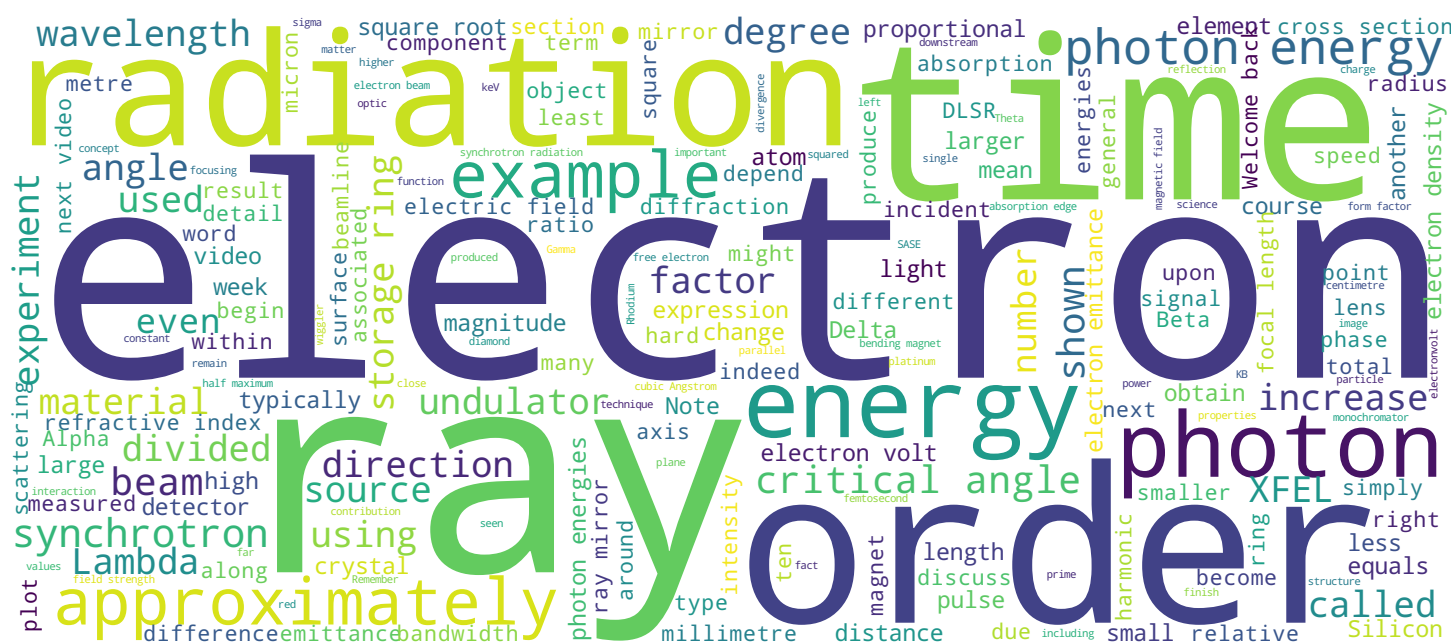


Synchrotrons and x-ray free-electron lasers

Techniques and applications

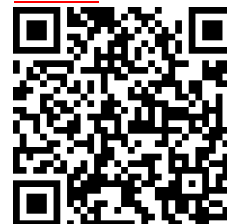
Prof. Philip Willmott



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Video



Contents and objectives of this video



- Mirrors
 - Types
 - Coatings
 - Absorption edges
 - Limits to performance
 - Roughness
 - Slope errors

Welcome back. In this shortish video, we will review the different types of mirror commonly available for X-ray reflection collimation and focusing, and how the usable photon range can be extended using coatings on the mirror surface. We finish by taking a semi-quantitative look at the figures of merit commonly cited for mirrors, namely the slope error and surface roughness.

Notes

Summary



0m 05s

Types of x-ray mirrors



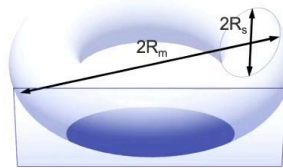
Flat



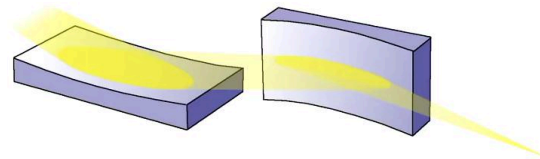
Fixed radius,
ground cylindrical or parabolic/elliptical



Dynamic focussing, flexure system



Toroidal



Kirkpatrick-Baez (KB)

X-ray mirrors come in various forms. The simplest is the flat mirror used to reflect and also suppress higher photon energies. A mirror made from Silicon with a width and height of 50 millimetres and the length of 60 centimetres has a mass of around three and a half kilogrammes. Remember also that meridional bending radii to focus X-radiation are measured in several kilometres. This means that mirrors with even this relatively modest mass usually need to be supported so that they do not sag under their own weight and induce an unintentional focus. Reflection of X-rays is achromatic, and, according to ray optics, is purely determined by the physical geometry. In other words, by the angle of incidence. All X-rays, at least up to energies that have their critical angles that remain above the instant angle, will be reflected in the same manner. Fixed focal length ground mirrors are therefore very interesting and easy to implement at a beamline that uses a well-defined range of photon energies. Grinding a cylindrical or spherical surface is relatively straightforward. Parabolic and elliptical surfaces are much more demanding and concomitantly more expensive.

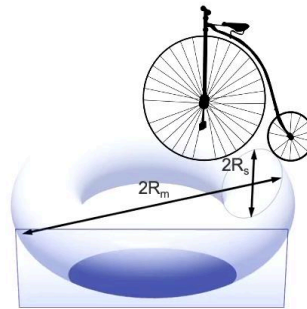
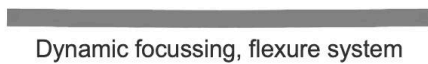
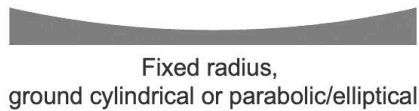
Notes

Summary

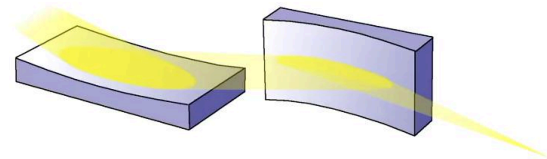


0m 32s

Types of x-ray mirrors



Toroidal



Kirkpatrick-Baez (KB)

Beamlines that require changes in the focal length of a curved mirror, such as those with more than one end station, can profit from variable focus mirrors using a Fletcher system. Simultaneous horizontal and vertical focusing can be achieved using a reflecting toroidal surface. This is the form produced by the inside surface of a toroid or in common parlance, the shape of a bicycle inner tube. Sagittal focusing is achieved by the curvature of the tube's cross-section, meridional focusing by the radius of the bicycle wheel, so to say. In the schematic shown here, the difference in magnitude between R_M and R_S is perhaps a factor of four. In reality, this ratio is more like 10,000 to 100,000. The photograph on the right of a real toroidal mirror clearly shows the sagittal curvature measured in centimetres. While the meridional radius is so large that the curvature cannot be discerned. So-called Kirkpatrick-Baez, or KB mirrors divide up the job of horizontal and vertical focusing into two elements imbuing KBs with added flexibility, though at the cost of increased space. An obvious problem with KBs is therefore that the demagnification factor of a KB is limited by the physical extent of the downstream element.

Notes

Summary



2m 00s

Types of x-ray mirrors



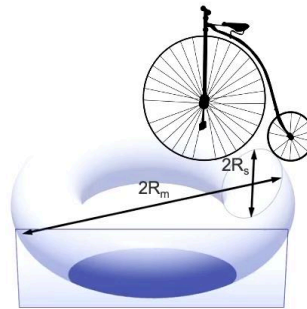
Flat



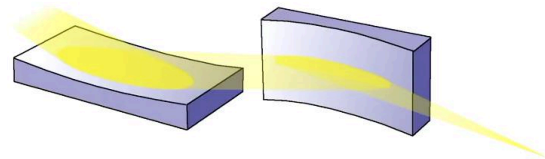
Fixed radius,
ground cylindrical or parabolic/elliptical



Dynamic focussing, flexure system



Toroidal



Kirkpatrick-Baez (KB)

The focal point of the upstream element needs to be downstream of the downstream element, as each element is typically a few tens of centimetres long a demagnification factor P divided by Q of more than about 50, is at most beamlines impractical using a KB.

Notes

Summary



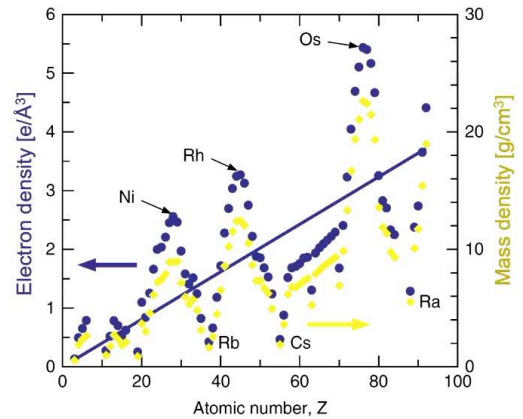
3m 35s

Mirror coatings

$$\left. \begin{aligned} \alpha_c &= \sqrt{2\delta} \\ \delta &= \frac{\rho r_0}{2\pi} \lambda^2 \end{aligned} \right\} \Rightarrow \alpha_c \propto \lambda \propto 1/h\nu$$

▪ e.g. silicon mirror

- $\rho = 0.6994 \text{ e}/\text{\AA}^3$
- $\delta = 3.139 \times 10^{-6} (\lambda [\text{\AA}])^2$
- $\alpha_c = 0.00251 (\lambda [\text{\AA}]) [\text{radians}]$
- e.g. $h\nu = 12.4 \text{ keV}, \lambda = 1 \text{ \AA}$
 - $\alpha_c = 0.00251 \text{ rad} = 0.1436^\circ$
 - Beam vertical FWHM @ first mirror $\approx 1 \text{ mm}$
 - Capture $\pm 1 \text{ FWHM}$
 - Mirror must be at least $2 \text{ mm}/0.00251 \text{ rad} \approx 800 \text{ mm}$



$$\alpha_c [\text{deg.}] = \frac{\sqrt{Z}}{30} \lambda [\text{\AA}]$$

The most common bulk materials from which X-ray mirrors are fabricated are Silicon and fused silica or SiO_2 . The electron density of Silicon is 0.7 electrons per cubic Angstrom. Using our known expressions for the refractive index decrement Δ and the critical angle, we obtain for Silicon an expression for α_c of 2.505 times λ in milliradians, if λ is expressed in Angstroms. Typically, one would like to capture and reflect at least two full-width half maximums of the beam. In the vertical direction, the beam's full width half maximum might be about a millimetre, meaning that the mirror must be at least a length of two millimetres divided by 2.505 times 10 to the minus three λ . For one Angstrom radiation, this means a mirror length of 800 millimetres. This is a long mirror. Because the critical angle is proportional to λ and therefore inversely proportional to the photon energy. 0.5 Angstrom radiation reflected from a Silicon mirror would need to be 1.6 metres long. This is a fairly tall order.

Notes

Summary



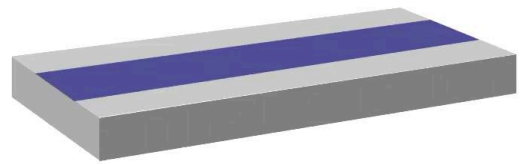
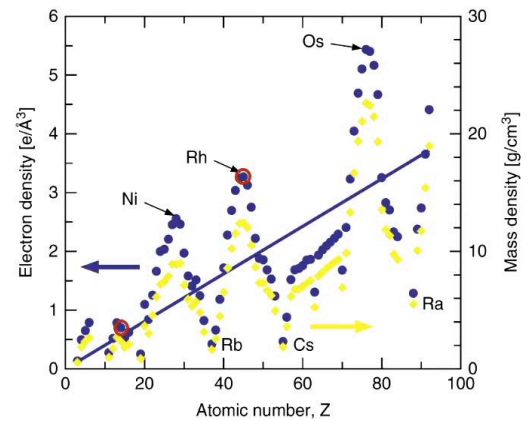
3m 56s

Mirror coatings

$$\left. \begin{aligned} \alpha_c &= \sqrt{2\delta} \\ \delta &= \frac{\rho r_0}{2\pi} \lambda^2 \end{aligned} \right\} \Rightarrow \alpha_c \propto \rho^{1/2}$$

▪ e.g. rhodium coating

- $\rho = 3.265 \text{ e}^-/\text{\AA}^3$
- $\delta = 1.465 \times 10^{-5} \text{ @ } 1 \text{ \AA}$
- $\alpha_c = 0.00541 \text{ rad } (0.31^\circ)$
 - Beam vertical FWHM @ first mirror $\approx 1 \text{ mm}$
 - Capture $\pm 1 \text{ FWHM}$
 - Mirror must be at least $2 \text{ mm}/0.00541 \text{ rad} \approx 370 \text{ mm}$



But we can ameliorate this problem by realising that the critical angle is also proportional to the square root of the electron density. Silicon might have a low electron density of approximately 0.7 electrons per cubic Angstrom, but other elements have substantially high electron densities, such as Rhodium with a value of 3.27 electrons per cubic Angstrom, over a factor of four higher than that for Silicon. So we can coat a strip of the Silicon mirror with a layer of Rhodium to a thickness that the incident X-rays do not see the underlying Silicon substrate. This increases the critical angle by the square root of the ratio of their electron densities, a factor of 2.16 in this instance, and reduces the necessary length by the same factor.

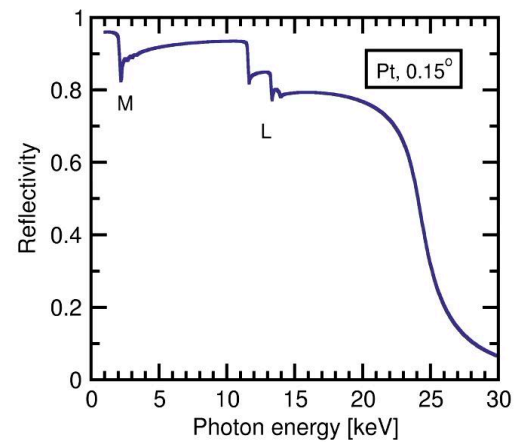
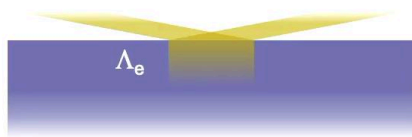
Notes

Summary



Mirror coatings and absorption edges

- Energy has $\alpha_c > \alpha_{inc}$
- But absorption edges
 - Evanescent wave penetrates \sim nm into surface Λ_e
 - Grazing angle
 - Absorption along ca. $\Lambda_e/\alpha_{inc} \sim 200$ nm
 - Reduced reflectivity



I just said that any high-density coating deposited on a low-density substrate, such as Rhodium on Silicon in order to increase the critical angle for total external reflection needs to be thick enough so that the X-rays do not see the underlying substrate. This implies that even in the case of radiation that is totally reflected, the X-rays must penetrate into the material to some kind of depth. This seems kind of logical, as if this were not the case, how could the X-rays be reflected at all? As they would not even interact with the mirror material. Now it emerges that indeed reflected waves do penetrate down into the material with an exponentially decaying evanescent standing wave with a decay depth given by Λ_e measured in nanometers. If the beam impinges at an angle lower than the critical angle for the photon energy being used, but if the photon energy is such that the beam would be strongly absorbed by the bulk material, then the reflectivity will be reduced. The reflected wave enters the material at a glancing angle and interacts with the material for approximately a distance equal to twice the evanescent penetration depth divided by the incident angle in radians.

Notes

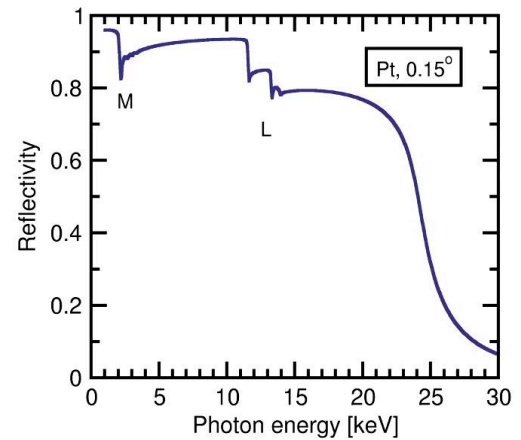
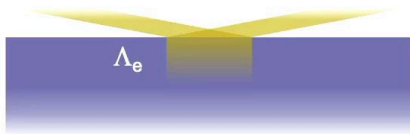
Summary



6m 14s

Mirror coatings and absorption edges

- Energy has $\alpha_c > \alpha_{inc}$
- But absorption edges
 - Evanescent wave penetrates \sim nm into surface Λ_e
 - Grazing angle
 - Absorption along ca. $\Lambda_e/\alpha_{inc} \sim 200$ nm
 - Reduced reflectivity



See, for example, the plot here of reflection of platinum at an instant angle of 0.15 degrees. The reflectivity drops significantly, yet the M and L edges of platinum at approximately two and 11 and a half to 14 keVs, respectively. Such absorption edges should thus be considered when designing an X-ray mirror for a given beamlines specifications, particularly regarding the energy range.

Notes

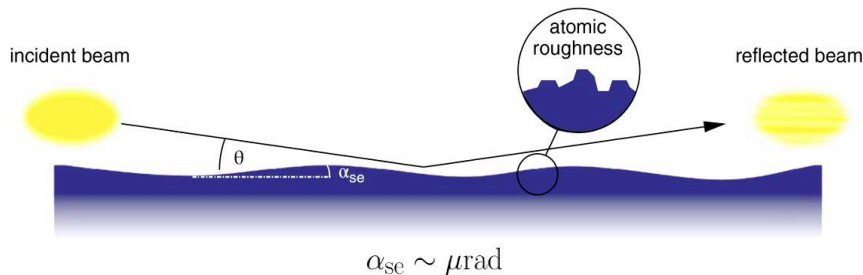
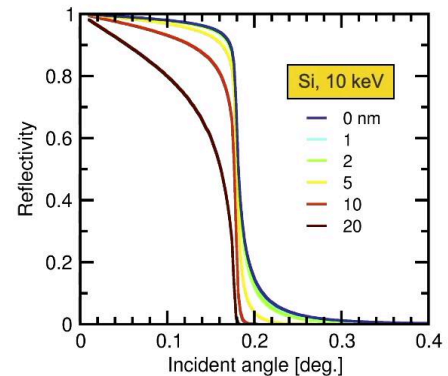
Summary



7m 42s

Mirror quality

- Atomic roughness
 - Variations within coherence lengths in plane of the mirror
 - Poorer reflectivity below α_c
 - Steeper drop-off above α_c
- Slope error
 - “Wobbliness” over macroscopic length scales distort beam profile



Remember from the second week of this course that the effective electron density, as seen by the X-rays, drops at absorption edges due to a decrease in F_1 . Consequently, the critical angle will also drop, because, as we have just said, it is proportional to the square root of the electron density. We see here, for example, that the critical angle for platinum at two keV is approximately two degrees. At the N edge just a couple of hundred electron volts higher, this drops temporarily to less than 0.4 degrees. If one were to scan this photon energy range in an experiment and one used a platinum-coated mirror, some anomalous behaviour would be observed. There are two important parameters that define X-ray mirror quality. First, the mirror surface must be flat on an atomic level, at least within the longitudinal and horizontal transverse coherence lengths. A significant atomic roughness results in poorer reflectivity below the critical angle and a steeper drop off above Alpha C. The slope error quantifies the wobbliness of the mirror on a macroscopic length scale and is typically of the order of a micro radian. The improved quality of radiation produced at DLSRs is pushing firms that fabricate such mirrors to push now for sub-micro radian specifications. This is another example of technological developments in one sector, driving improvements in another.

Notes

Summary



In the next video...



In the next video, we will briefly overview monochromators in general before detailing different monochromator types in the next but one video.

Notes

Summary



10m 01s