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New technique for aberration diagnostics and alignment of an extreme ultraviolet Schwarzschild objective

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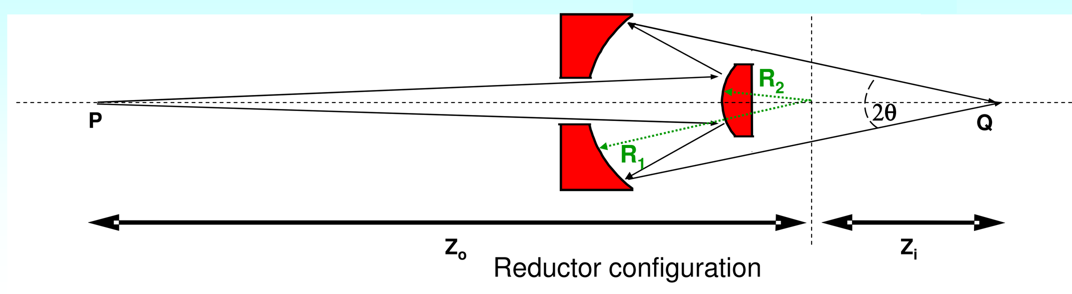
Limiting factors for Schwarzschild Objective spatial resolution and test

The Schwarzschild Objective (SO)



Schwarzschild objectives (SO) are widely used in the extreme ultraviolet (EUV) and soft X-ray spectral regions both as magnification and reduction optics, e.g. for microscopy and small-field projection lithography, respectively. The ENEA SO is used in the second configuration.

A SO consists of two spherical mirrors (one concave, the other convex) put in concentric configuration. It is possible to determine a pair (P,Q) of conjugated points on the optical axis where the aberrations are dramatically reduced and the attainable spatial resolution from a geometric point of view is comparable with the diffractive one.

ENEA SO parameters: R_1= 144.23 mm, Z_o= 340.22 mm, Z_i= 36.26 mm, R_2= 45.06 mm, Φ_1= 74 mm, Φ_2= 12.7 mm

M=1/9.5
NA=n·sinθ=0.23
λ = 14.4 nm

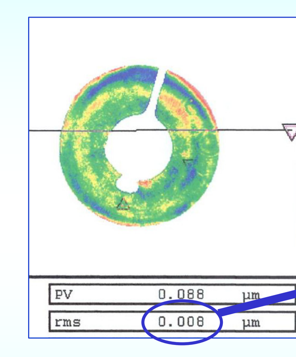
A.Budano, F.Flora, L.Mezi, **Appl. Opt. 45, 4254-4262 (2006)**
S.Bollanti, P.Di Lazzaro, F.Flora, L.Mezi, D.Murra, A.Torre, **Appl. Phys. B 85, 603–610 (2006)**

The objective spatial resolution

Several factors affect the optics spatial resolution δ. For each factor the ENEA-SO δ value is given below.

DIFFRACTION $\delta_{diff} = k \cdot \lambda / NA$ → δ_{diff} = 38 nm

FIGURE ERROR → SO figure error rms = 8 nm

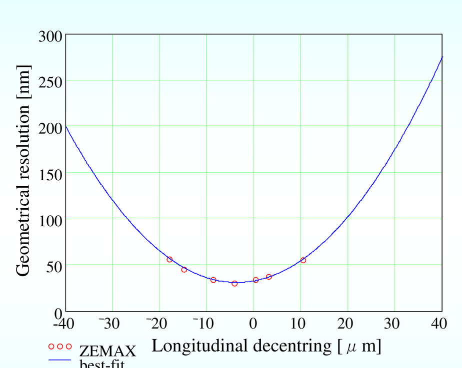


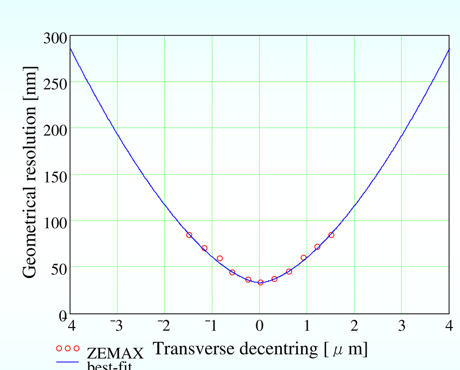
OPTICAL ABERRATIONS (↗ with NA) e.g. spherical, coma → Aligned SO ⇒ δ_{geo} = 27 nm (in modified configuration)

It can be much worse if the **ALIGNMENT** is not correct

The SO misalignment sensitivity

The ray-tracing program ZEMAX allows to relate the SO mirrors misalignment to the worsening of the geometrical resolution (defined as the minimum rms diameter of the image of a point source on the optical axis).





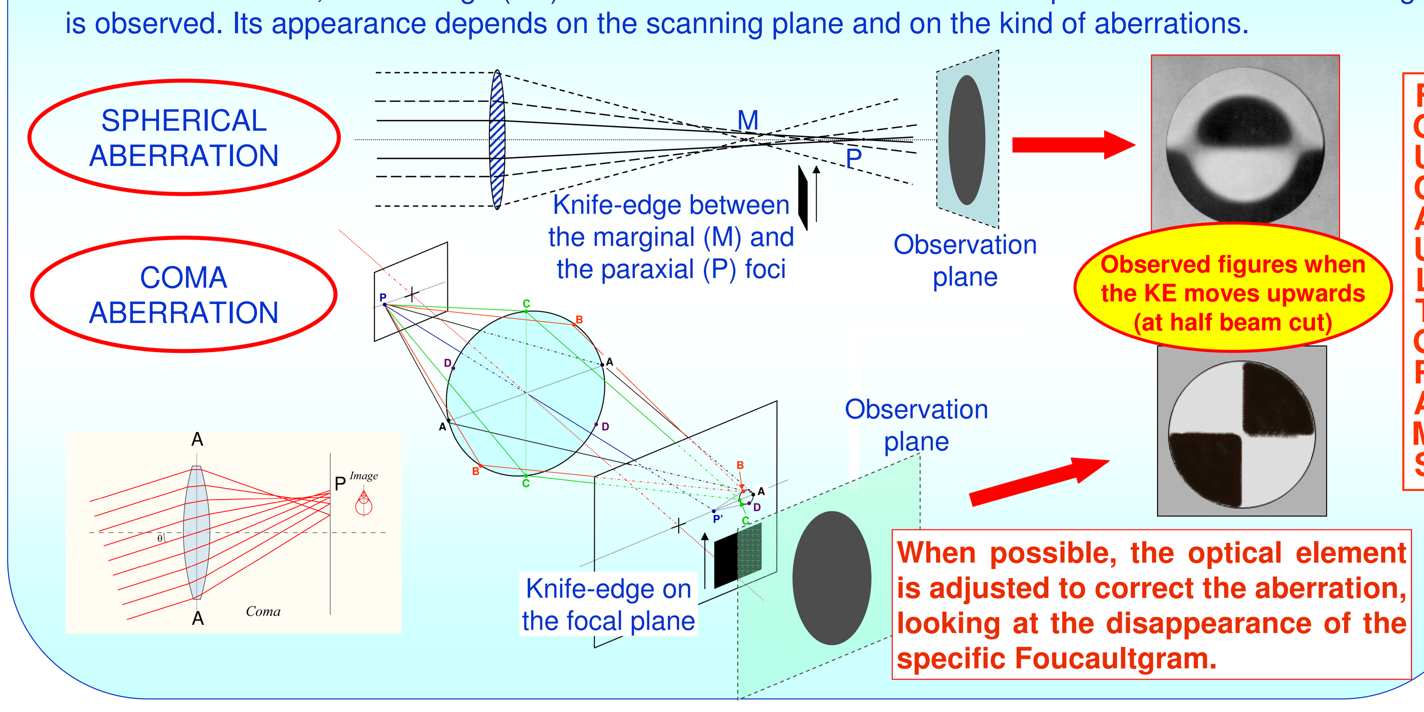
The **longitudinal decentring** of the two mirrors influences the on-axis aberration, i.e. the spherical one.

The **transverse displacement** of the mirrors' centres mainly generates the coma aberration, because this condition corresponds to having an off-axis source. A 1-µm displacement is generated by a 7-µrad tilt of the concave mirror with respect to the optical axis

S.Bollanti, P.Di Lazzaro, F.Flora, L.Mezi, D.Murra, A.Torre, **Appl. Phys. B 91, 127–137 (2008)**

The aberration diagnostics with the Foucault test

In the Foucault test, a knife edge (KE) is scanned across the beam and the pattern of the transmitted light is observed. Its appearance depends on the scanning plane and on the kind of aberrations.



When possible, the optical element is adjusted to correct the aberration, looking at the disappearance of the specific Foucaultgram.

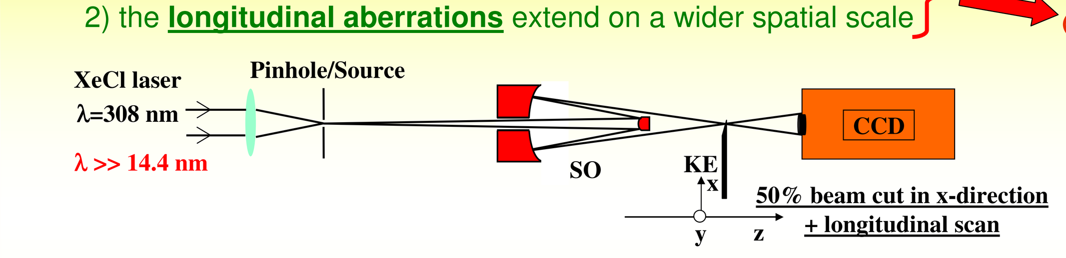
Foucault test improvement to overcome diffraction limitation

Longitudinal scan and geometrical figures

The "classical" transverse KE scan is replaced by a **longitudinal scan** with a 50% beam cut since:

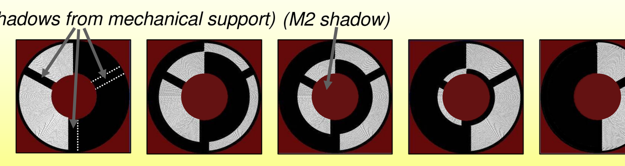
1) during the scan the transmitted power is almost constant
2) the **longitudinal aberrations** extend on a wider spatial scale

→ HIGHER SENSITIVITY TO MISALIGNMENT

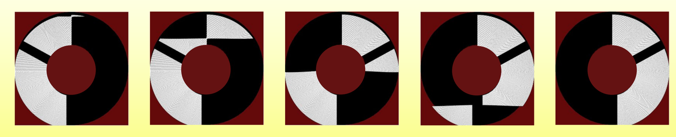


Calculated Foucaultgrams for spherical aberration (by ray tracing)

(Shadows from mechanical support) (M2 shadow)



Calculated Foucaultgrams for coma aberration (mirror rotation axis || x)

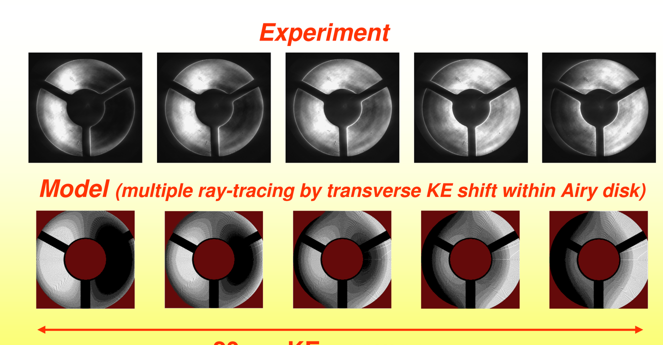


Ultraviolet light and diffraction

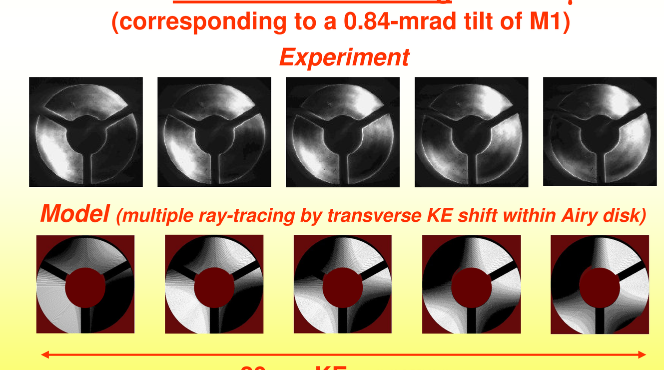
When the transverse dimension of the beam is comparable with λ/NA, diffraction effects prevent any further improvement:

- The effect of the "long"-wavelength-light diffraction in the plane of KE cutting smears out the foucaultgrams calculated in geometrical approximation
- The observed images are blurred and put a limit on the minimum detectable aberrations

Mirrors longitudinal decentring of ~ -350 µm



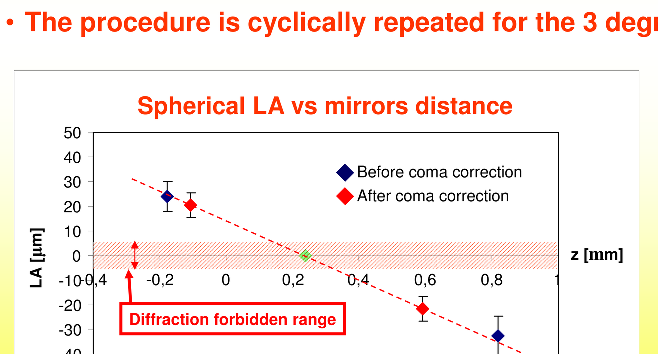
Mirrors transverse decentring of ~ 120 µm (corresponding to a 0.84-mrad tilt of M1)

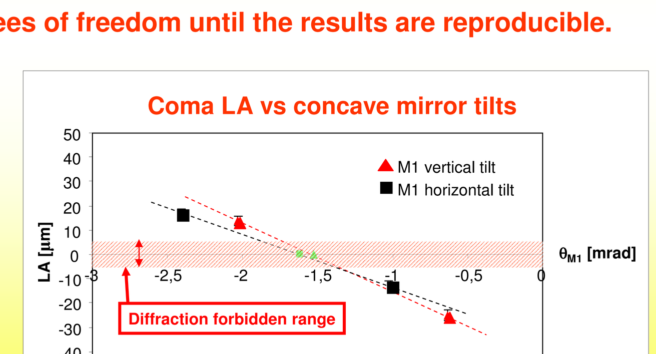


P.Di Lazzaro, S.Bollanti, F.Flora, L.Mezi, D.Murra, A.Torre, **IEEE Trans. Plasma Sci. 37, 475-480 (2009)**

Controlled misalignment and interpolation

- The SO has 3 degrees of freedom for alignment: the distance between mirrors and the rotations of the concave mirror around two mutually orthogonal axes crossing each other at the mirror vertex.
- The longitudinal aberrations (LA) are measured as function of these parameters outside the diffraction forbidden region, looking at the foucaultgrams obtained varying the parameters one at a time.
- The optimum position of the SO mirrors can be found by means of interpolation for each parameter.
- The procedure is cyclically repeated for the 3 degrees of freedom until the results are reproducible.

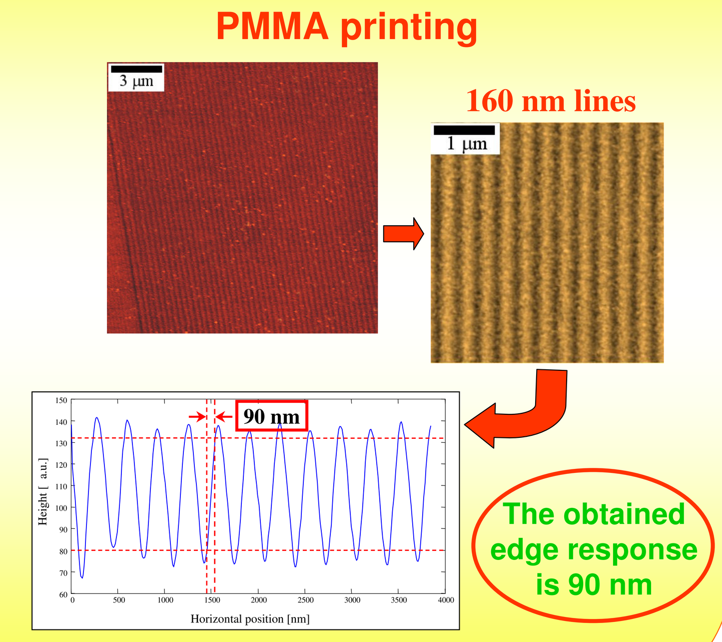




Final SO performances and conclusions

- The alignment of a Schwarzschild objective operating at EUV wavelength is a very critical task
- The attainable spatial resolution is strictly related to a correct alignment
- We demonstrated that aberrations diagnostics and correction using a wavelength that is ~20× the operating one to align a SO are possible through the described procedure
- The aligned SO has been used as the projection optics in the EUV MET-Egeria facility in the ENEA Frascati Research Centre to print 160-nm-width dense lines on PMMA photoresist

PMMA printing



The obtained edge response is 90 nm

S.Bollanti, P.Di Lazzaro, F.Flora, L.Mezi, D.Murra, A.Torre, **EPL, 84 (2008) 58003**