

EuroFEL: FEL mirrors and calibration spheres

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Outline



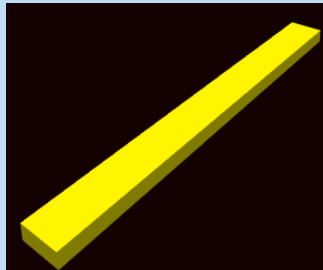
- Fabrication examples
 - » Mirrors for xFELs: Bending mirrors of various geometries
- Spheres
 - » What we can learn from sets of identical spheres for xFELs mirrors
- Status
 - » State-of-the-art metrology and manufacturing from the manufacturers point of view
- Summary

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Fabrication examples FEL mirrors (bending mirrors)



thin bending mirror

- thickness $10^{-0.1}$ mm
- tangential radius of flat mirror > 300 km



flat KB mirror pair

- flat mirrors for bending application
- freeform substrate width distribution



set of 4 tangential cylinders

- residual slope errors (< 0.25 μ rad rms)
- figure specification (< 2 nm rms)

Thin bending mirror



Features		Specification / Manufacture
Material	Fused silica HOQ310	
Dimensions	400 x 40 x 10 mm ³	
Clear aperture	360 x 20 mm ²	
Properties	Specification	Results
Dimensions	400 +0/-1 x 40 +0/-0.5 x 10 +0/- 0.2 mm ³	399.72 x 39.84 x 9.91 mm ³
Geometry	minimum radius: > 5 km	R > 300 km (convex) ⁽¹⁾
Slope Error	tangential: < 0.50 μrad rms	0.20 μrad rms ⁽¹⁾
	sagittal: < 5.00 μrad rms	0.80 μrad rms ⁽¹⁾
Shape Error	< 10.0 nm pv area: 70 x 20 mm ²	5.43 - 9.87 nm pv ⁽¹⁾
Surface Roughness	MSFR: 2-500 μm ≤ 0.3 nm rms	0.26 – 0.29 nm rms ⁽²⁾
		0.21 – 0.26 nm rms ⁽³⁾
		PSD: 0.253 nm rms

Challenge:

do large aperture tool polishing on thin substrate.

mounting errors manifest itself as long wave figure error

Thin bending mirror



For bending mirrors absolute metrology becomes essential:

- Checking the dimensions, tilt and relative orientation of faces
- Checking clamping features such as bores and grooves

Absolute metrology : UPMC

- Commercially available 3D CMM Metrology
- For large scale absolute measurements (< 1m)
- accuracy $0.3 \mu\text{m} + 0.1\mu\text{m}/100 \text{ mm}$



Thin bending mirror

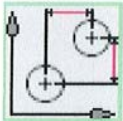
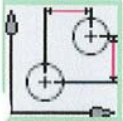
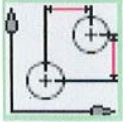


Example: Determine dimensions of thin bending mirror in the sub micro level.

length

width

height

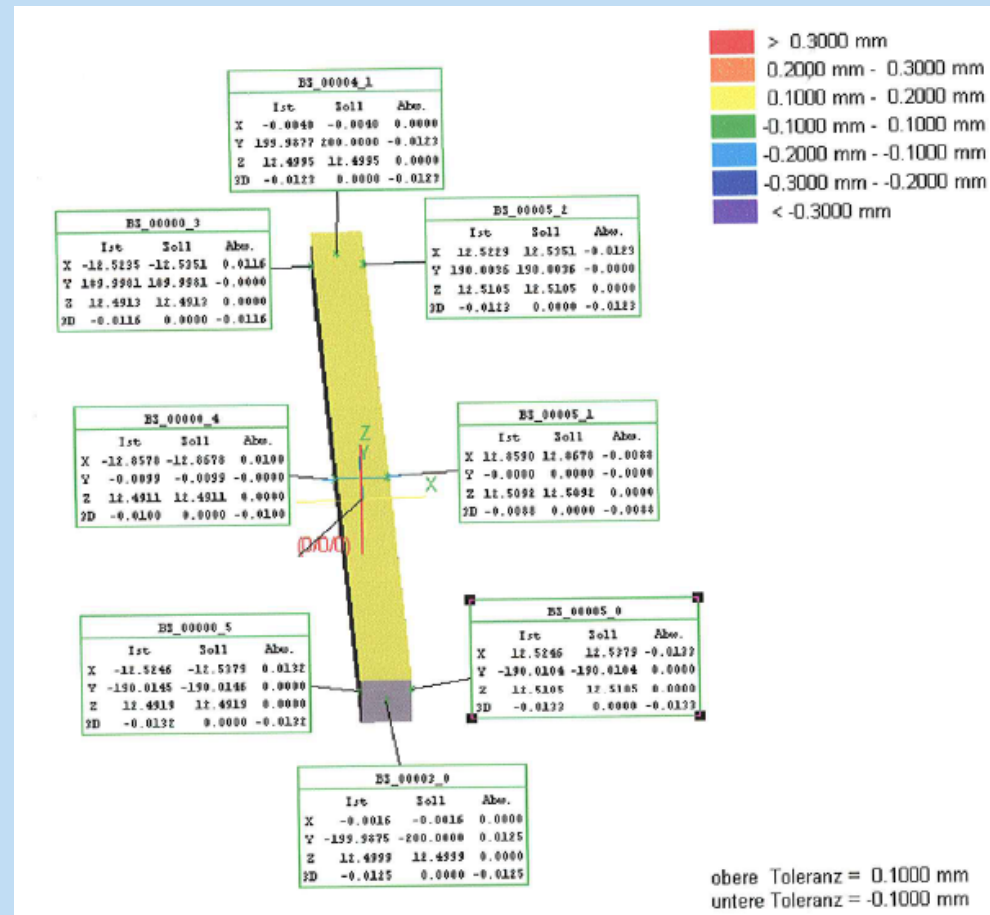
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	Distanz kart.2 39.84269	40.00000	0.00000	-0.50000	- -0.15731
	Distanz kart.3 9.90785	10.00000	0.00000	-0.20000	- -0.09215

KB bending mirror: multiple tolerances



flat KB mirrors for bending applications:

- Multiple tolerances
 - » front and end faces parallel to 0.025 mm
 - » front/end faces perpendicular to upper/lower face 0.025 mm
- Variable width over the entire length
 - »M1 1 mm variation
 - »M2 2 mm variation
 - »tolerance shape 0.05 mm
 - »parallel side faces 0.025 mm
- chamfers and faces radii



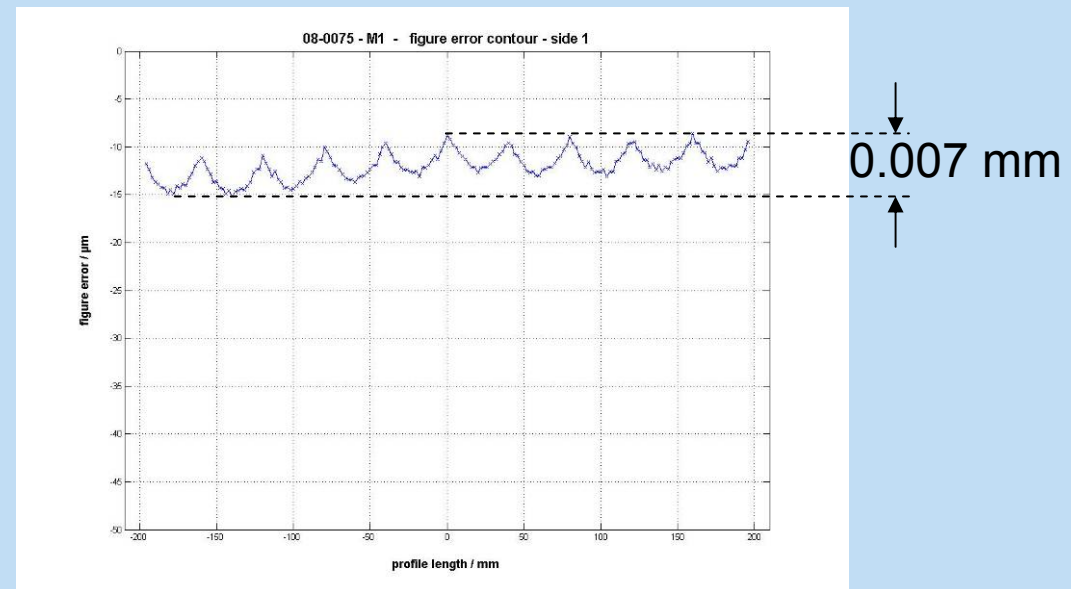
KB bending mirrors: side faces with freeform width



Use precision CMM Zeiss UPMC 850 S-ACC Carat for absolute determination of substrate geometry properties



Example for side face measurement:
Departure from designed face < 0.01 mm



KB bending mirrors: summary



	ALS profile center	Zeiss clear aperture	ALS curvature	Zeiss curvature	Zeiss roughness	sagital slopes
unit	μrad RMS	μrad RMS	km	km	nm RMS	μrad RMS
spec	0.25	0.25	> 100	> 100	0.5	2.5
M1	0.15	0.22	240 concave	300 concave	0.11-0.13	1.07
M2	0.15	0.25	1300 convex	> 500 convex	0.11-0.13	1.10

Results Zeiss and ALS (OML)

- tangential slope errors below 0.25 μrad RMS for clear aperture
- tangential radius > 165/300 km
- height error below 1.6/1.3 nm RMS
- roughness MSFR 0.11- 0.13 nm RMS
- all substrate dimensions within specifications
- side face freeform figure error < 0.01 mm

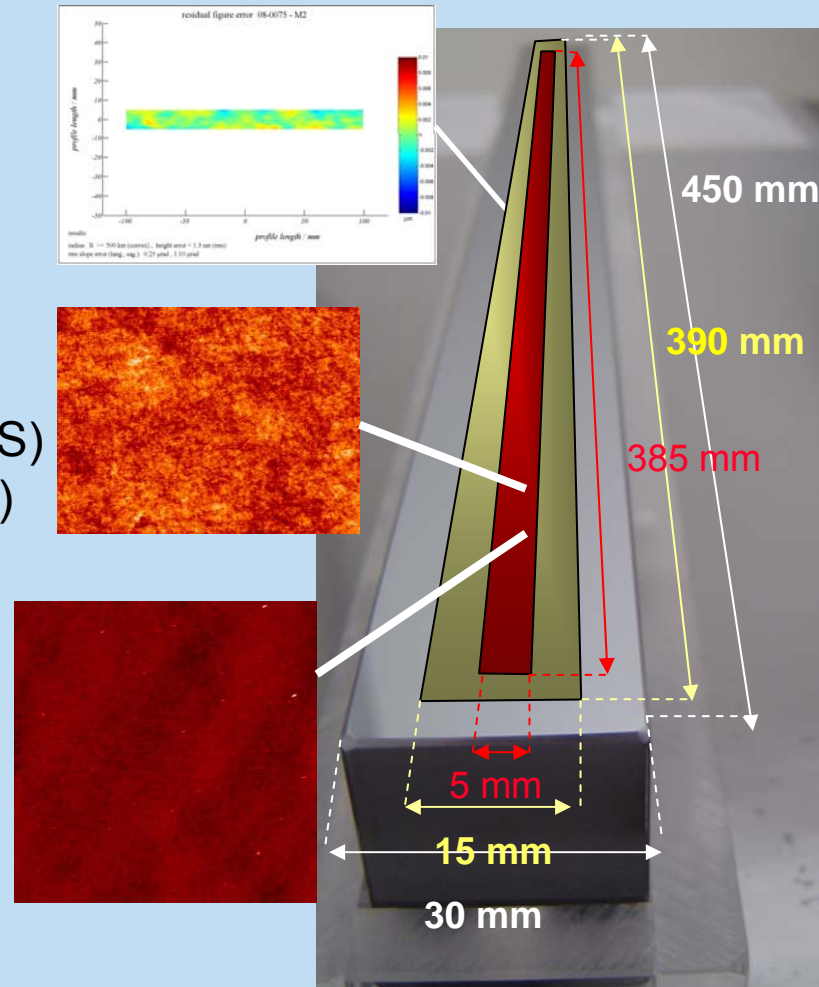
Very good agreement of ALS optics Lab and Zeiss on profile results 0.15 /0.16 μrad RMS

HOMS mirrors



Set of 4 tangential cylinders

- substrate dimensions 450 x 30 mm²
- specification for clear aperture
 - zone 2: 430 x 15 mm²
 - zone 1: 385 x 5 mm²
- residual slope errors (< 0.25 μrad RMS)
- tight figure specification (< 2 nm RMS)
- full roughness specification:
 - MSFR
 - HSFR
- Tight radius tolerance (150 km < R < 195 km)



HOMS mirrors: summary for #4



#4	radius	height error		slope		μ-roughness	
	tangential	zone 1	zone2	tangential	sagittal	MSFR	HSFR
units	km	nm RMS		μrad RMS		nm RMS	
specification	150-195	2.0	5.0	2.00	5.00	0.25	0.40
results	170	0.98	1.35	0.09	0.46	0.12-0.13	0.12-0.32

Excellent tangential slope errors below 0.1 μrad for zone 1 and 2

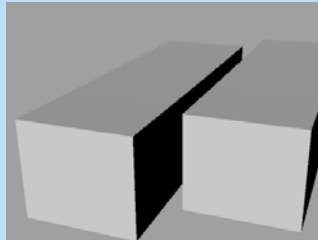
- height error below 1 nm RMS for zone 1
- roughness MSFR 0.2 nm, HSFR 0.2 nm RMS
- excellent agreement of metrology between LLNL and Zeiss for
 - » figure (interferometer results)
 - » roughness MSFR and HSFR (AFM and μ-interferometer)

Outline



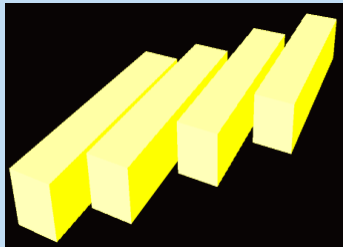
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Sets of identical spheres



Set of 2 calibration spheres (HZB/BESSY)

- Radius 9300 mm
- Sphere #1 slope error 0.174 μ rad RMS



set of 4 calibration spheres

- Radius 370 m +/- 2%
- Slope error 0.2-0.5 μ rad RMS

Sets of identical spheres (1)



Features	Specification / Manufacture
Material	Si <100>
Dimensions	145 x 45 x 40 mm ³
Clear aperture	120 x 50 mm ²

sphere No.	radius	figure	slope	roughness
	mm	nm RMS	μrad RMS	nm RMS
Spec	9300 +/- 2 %		1.0	1.0
#1	9318 / 9312 (NOM)	1.69/ 0.88 (NOM)	0.174 (NOM)	0.14
#2	9322	0.97		0.18

The radii of the two calibration spheres differ by less than 0.05% of the design radius of 9300 mm.

0.05% corresponds to approx. 80 nm departure from the design radius

Results achieved without any deterministic figuring !

Sets of identical spheres (1)

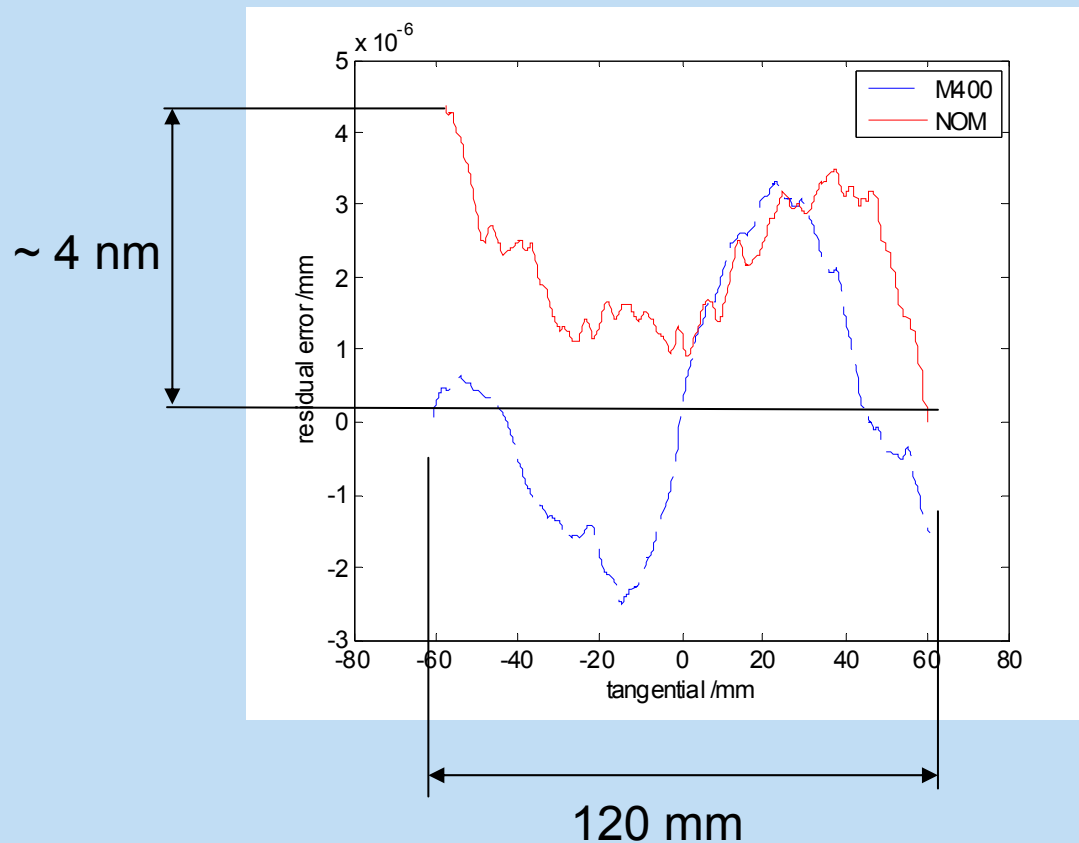


Long wave errors
= departure of radius from
design radius
wavelengths \sim clear aperture

Medium wave errors
= figure errors other than
spherical
wavelengths > 10 mm

Short wave errors
= ripple like structure
wavelengths: few mm

Medium wave errors on calibration
sphere #1 as seen by M400 and NOM



Sets of identical spheres (2)



Features		Specification / Manufacture
Material		ULE (premium grade)
Dimensions		100 x 20 x 20 mm ³
Clear aperture		90 x 15 mm ²
Coating		-----
Properties	Specification	Results
Geometry	spherical radius: $R = 370 \text{ m} \pm 2\%$ all substrates are to have the same radius: $\pm 0,5 \text{ m}$	$R_{\text{mean}} = 368.21 \text{ m}$ $R_{G1} = 368.68 \text{ m}$ $R_{G2} = 368.20 \text{ m}$ $R_{G3} = 368.21 \text{ m}$ $R_{G4} = 367.74 \text{ m}$
Slope error (rms)	tang. slope error: $< 0.5 \mu\text{rad (rms)}$	G1: $0.26 \mu\text{rad (rms)}$ G2: $0.22 \mu\text{rad (rms)}$ G3: $0.25 \mu\text{rad (rms)}$ G4: $0.42 \mu\text{rad (rms)}$
Surface Roughness (rms)	MSFR: $\leq 1.0 \text{ nm}, 10\mu\text{m} < \lambda \leq \text{mm}$	$0.27 - 0.33 \text{ nm}, 20\times$ $0.18 - 0.21 \text{ nm}, 2,5\times$

Challenge: Keep the radius for 4 substrates constant within 0.1 % = approx. 20 nm

Sets of identical spheres (2)



Results for the radii of individual spheres from M400 measurements

sphere #	Radius M400 /m	variation from mean /m	variation from design	% variation from mean	% variation from design
spec	370 m	0.5 m			2%
1	368.68	0.22	-1.32	0.06	-0.36
2	368.20	0.26	-1.80	0.07	-0.49
3	368.21	0.25	-1.79	0.07	-0.48
4	368.74	-0.28	-1.26	-0.08	-0.34

Mean radius 368.460

Height error PV of individual radii from design radius approx. 14 nm

Height error PV of individual radii from mean radius approx 2.5 nm

(Height errors calculated for a clear aperture of 100 mm length)

Sets of identical spheres current limitations for spheres and flats



- Length < 0.3 m without stitching (calibration < 1 nm RMS)
- Length < 1-1.2 m with stitching (calibration for long wave errors elaborate)
- Slopes may come off very well from polishing (< 0.2 μ rad RMS)
- Height error after polishing < 1 nm RMS feasible
- 0.8 m max. length for ultra precision figuring (Ion beam)
- Long wave geometry can be controlled very effectively: However absolute radius control much less accurate
- Long wave error control mostly depends on reproducibility of metrology
- Sagittal radius very difficult to determine due to typically short basis length
- Roughness 0.1-0.2 nm RMS

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Figure metrology options (as seen form a manufacturers point of view)



Profilers

- + slope resolution / accuracy
- + access to significant curved geometries, freeforms
- Large lateral measurement spot
- Long measuring times
- Only individual traces, no 2D information
- Needs substrates with high reflectance (e.g. SiO₂ with metallic coating only)
- Position detection needs special marks / fiducials

Metrology overview (Stitching- Interferometers) (as seen form a manufacturers point of view)



Interferometers

- + fast and efficient 2 D data recording
- + height accuracy
- + edge detection
- Inflexible to changing geometries
- access to off axis geometries elaborate/
limited
- Limited mostly to 12" without stitching

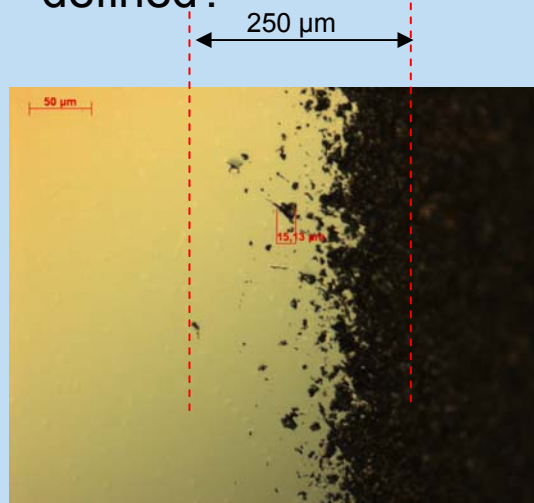


For figure measurements up to
300 mm aperture length, and
up to 1 m with stitching

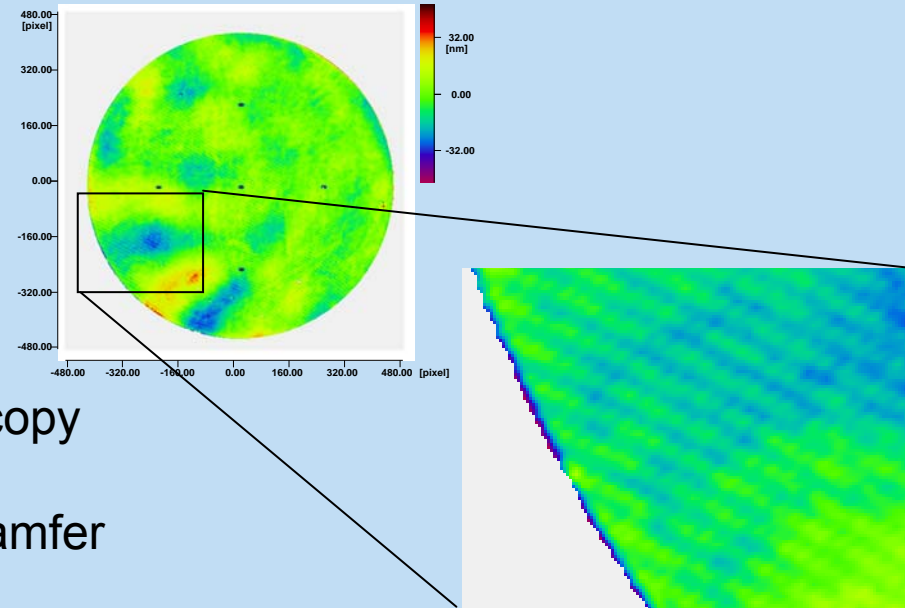
Figure metrology options (as seen from a manufacturers point of view)



How well are edges defined?



Left: microscopy picture of a standard chamfer near edge



Right: Interferogramm of circular optical mirror

Due to large number of „edge points“ in 2D interferograms positions within circular optical face are defined better 0.1mm.

Edge effect from single traces probably less accurate.

Figure metrology options (as seen form a manufacturers point of view)



Most profilers are operated at user facilities (mostly synchrotron optics labs)
High-end profilers and interferometers are not easily commercially available
Profilers are mostly used for verification, not for figuring

- No absolute positioning and orientation data

- Mirror edges/chamfers are usually not suitable for absolute positioning

- The mechanism for signal break off is not well analyzed

- Few experience with absolute positioning operation

- (ESRF and Zeiss will address this issue with a test mirror within a manufacturing project)

Limitations should be overcome for high-end optics since limited market volume will not encourage most optics manufacturers to invest in the full scope of high-end metrology

The best optics straight forward available in cooperation with industry

Fabrication examples from literature

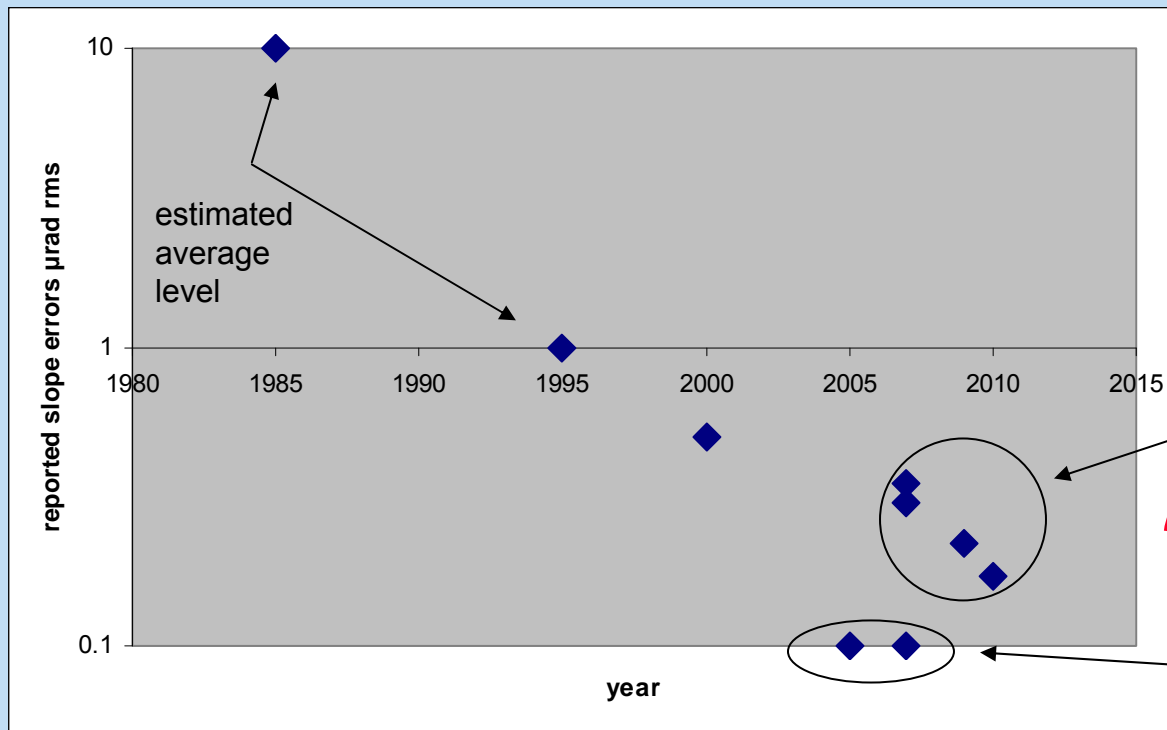


- 10 μrad mirrors were considered to be of excellent quality in the 80s (NSLS-I), 1 μrad mirrors in the 90's (APS, Spring-8), P. Taccas OSA / FiO/LS/META/OF&T, 2008
- 0.3 μrad / 900 mm – Silicon, Mirror size 1200x100x60 mm, ESRF, Rommeveaux (2007)
- Plane mirror Slope error Tangential 0.35 μrad RMS, FLASH, Tiedke (2007)
- EEM on 100 mm KB-mirror, 1-2 nm PV, 0.2 nm RMS, Yamauchi (2007)
- 0.22 μrad RMS substrate within the central 420 mm-length, A. Barty OPTICS EXPRESS 15519
- 0.17 μrad on 160 mm calibration sphere (Zeiss/BESSY 2010)

Fabrication overview from literature



Examples of reported slope errors starting from the 80's



Current state of the art for larger/more complex mirrors



small/flat

- Points for 80s and 90s represents some average level of slope error for x-ray mirrors
- 0.1 μrad RMS only for short and /or flat mirrors

What will be the FEL goal?



„In order to transmit the full brightness of the XFEL radiation to an experiment, reflective optical elements such as mirrors must have excellent figures ... These issues are currently being addressed at the facilities constructing XFELs. As these sources become operational, experience will be gained and practical solutions will be found.“

John Arthur Optics for xray FEL, (2005)

	LCLS	FERMI	EuroXFEL
Material	mono Si	SiO ₂ , Si	Si, SiC
Clear Aperture	100-600 mm	100-500 mm	800-1200 mm
Height error	< 1-2 nm RMS	< 5-10 nm PV	< 1 nm
Slope error	< 0.25 μ rad	0.5 μ rad RMS	?
Roughness	0.2-0.4 nm	0.3 nm	?
Geometry	flat or low curvature ellipses, bendable	mostly flat, bendable	Flat

Summary



- Capabilities
 - » Various geometries dimensions of bending mirrors for xFEL application realized
- Recent achievements
 - » low residual slope errors ($< 0.2''$ rms)
 - » low figure roughness (< 2 nm rms)
 - » Identicalness of spheres → long wave error in good control
- Metrology
 - » Metrology is frequently the deciding limitation for ultra precise mirror fabrication
 - » Positioning features for figuring and profiling under investigation



We make it visible.