Carl Zeiss SMT

EuroFEL: FEL mirrors and calibration spheres

H. Thiess [1], H. Lasser [1] and F. Siewert [2]

[1] Carl Zeiss Laser Optics

[2] HZB/BESSY

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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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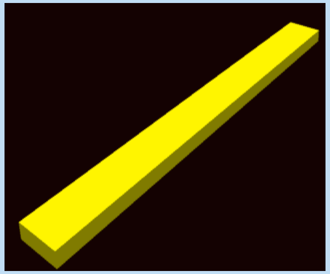
Fabrication examples FEL mirrors (bending mirrors)



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 µrad 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 sagittal: < 5.00 µrad rms	0.20 µrad rms (1) 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

- Comercially available 3D CMM Metrology
- For large scale absolute measurements (< 1m)
- accuracy 0.3 µm + 0.1µm/100 mm

Thin bending mirror

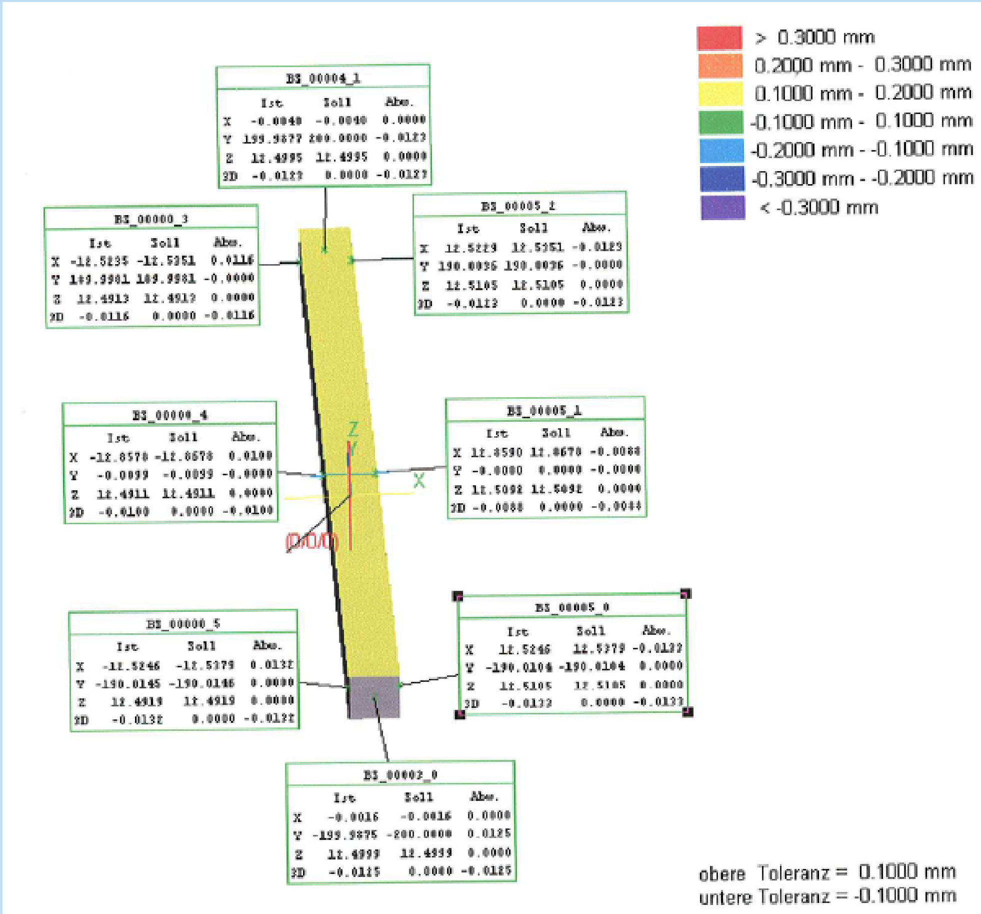
Example: Detemine dimensions of thin bending mirror in the sub micro level.

		Istwert	Sollwert	Obere Tol.	Untere Tol.	Abweichung
length	Distanz kart.1					|–
		399.71656	400.00000	0.00000	-1.00000	-0.28344
width	Distanz kart.2					|–
		39.84269	40.00000	0.00000	-0.50000	-0.15731
height	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

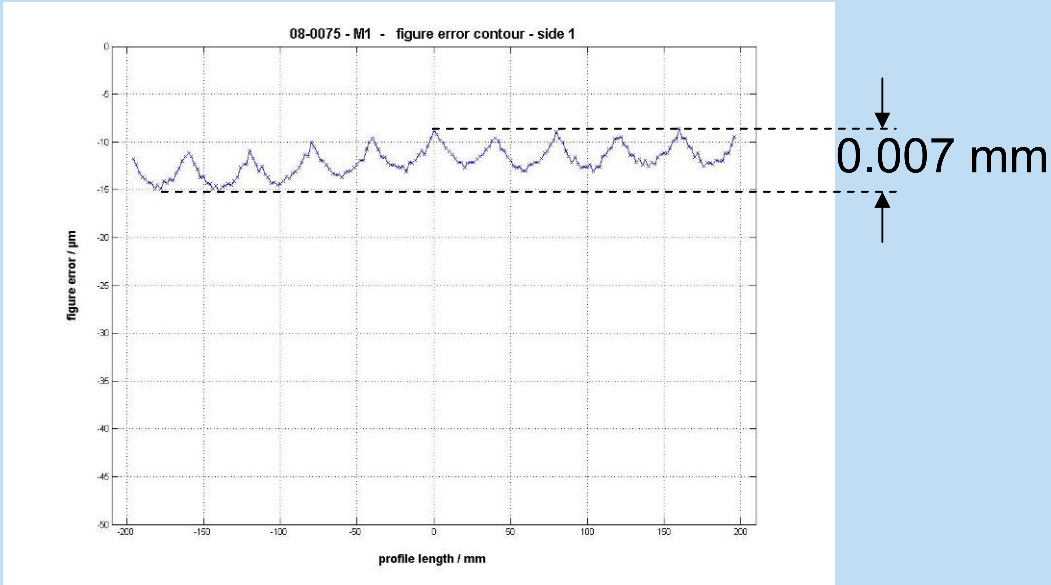


KB bending mirrors: side faces with freeform width

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)

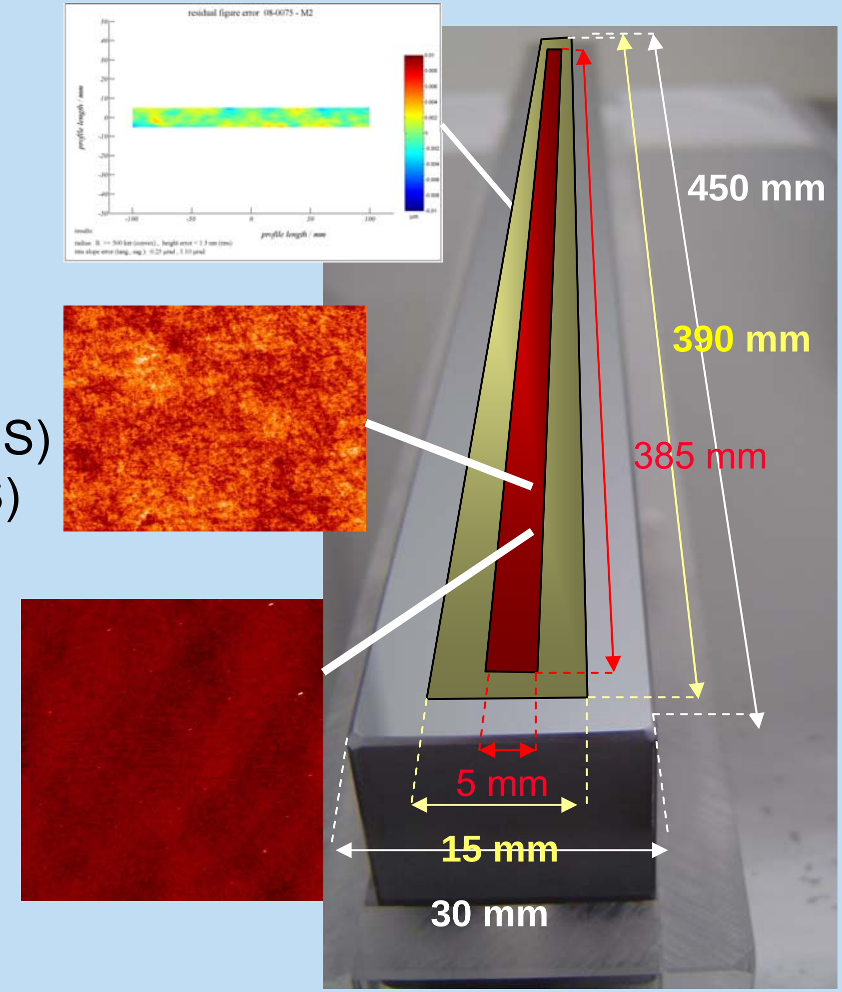
- tangential slope errors below 0.25 µrad RMS for clear aperture
- tangential radius > 165/300 km
- height error below 1.6/1.3 nm RMS
- roughness MSFR 0.11- 0.13 nm RMS
- all substrate dimensions within specifications
- side face freeform figure error < 0.01 mm

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)

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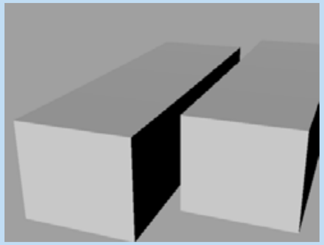
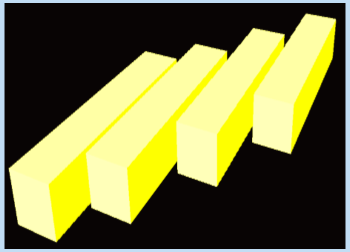
Sets of identical spheres



Set of 2 calibration spheres (HZB/BESSY)

- Radius 9300 mm
- Sphere #1 slope error 0.174 µrad RMS



set of 4 calibration spheres

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

Sets of identical spheres (1)

ZEISS

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 then 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 ~ clear aperture

Medium wave errors

= figure errors other than
  spherical

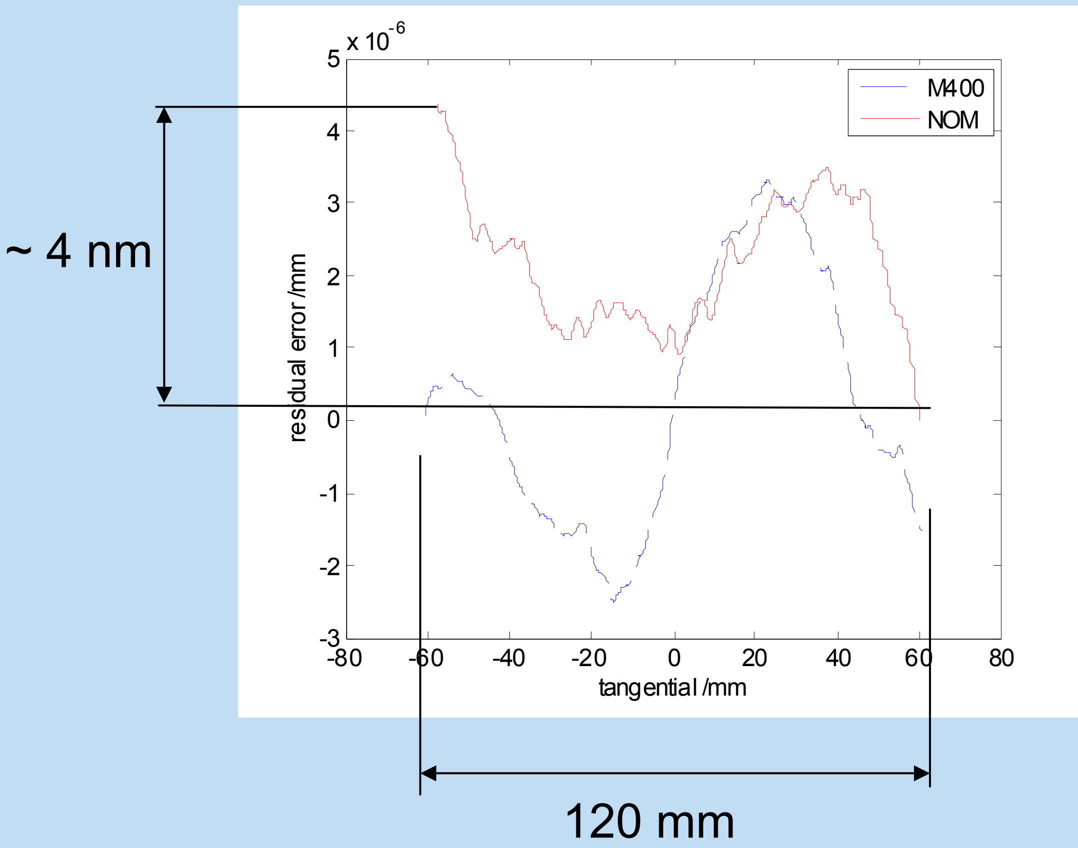
wavelengths > 10 mm

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 m +/- 2% all substrates are to have the same radius: +/- 0,5 m	R_{mean} = 368.21 m R_{G1} = 368.68 m R_{G2} = 368.20 m R_{G3} = 368.21 m R_{G4} = 367.74 m
Slope error (rms)	tang. slope error: < 0.5 µrad (rms)	G1: 0.26 µrad (rms) G2: 0.22 µrad (rms) G3: 0.25 µrad (rms) G4: 0.42 µrad (rms)
Surface Roughness (rms)	MSFR: ≤ 1.0 nm, 10µm < λ ≤ mm	0.27 – 0.33 nm, **20x** 0.18 – 0.21 nm, **2,5x**

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 µrad 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. SiO_2 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

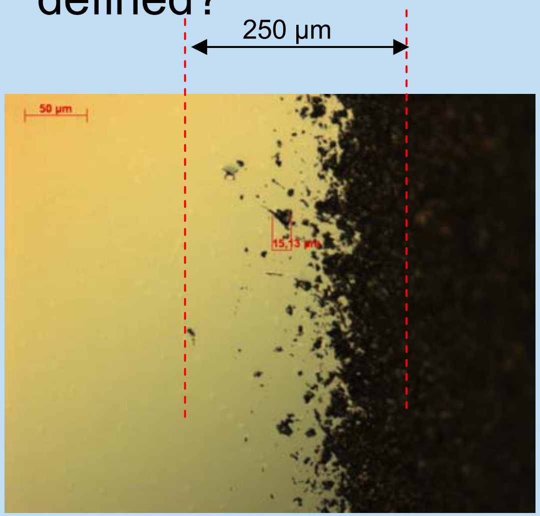
-access to off axis geometries elaborate/ limited

-Limited mostly to 12” without stitching

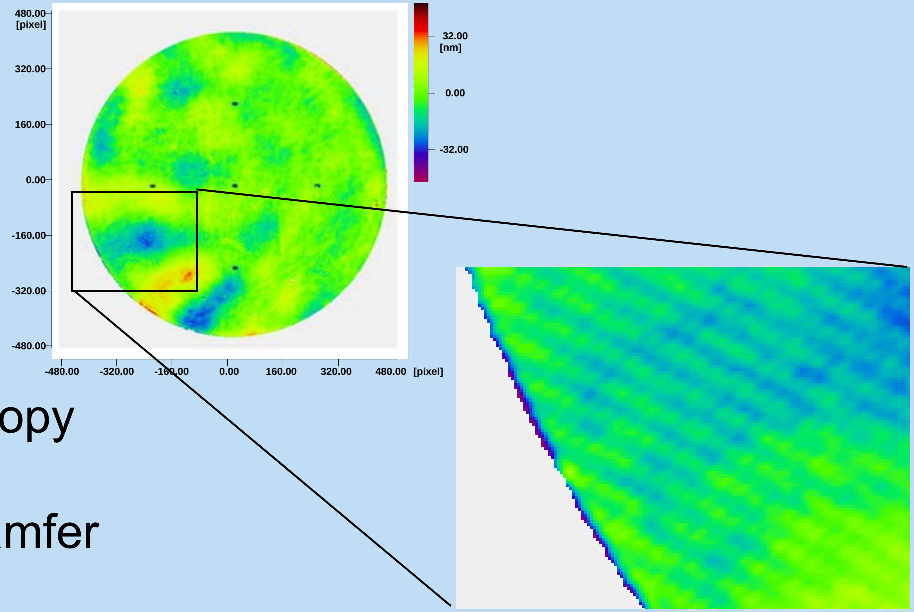
For figure measurements up to 300 mm aperture length, and up to 1 m with stitching

Figure metrology options
(as seen form 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)

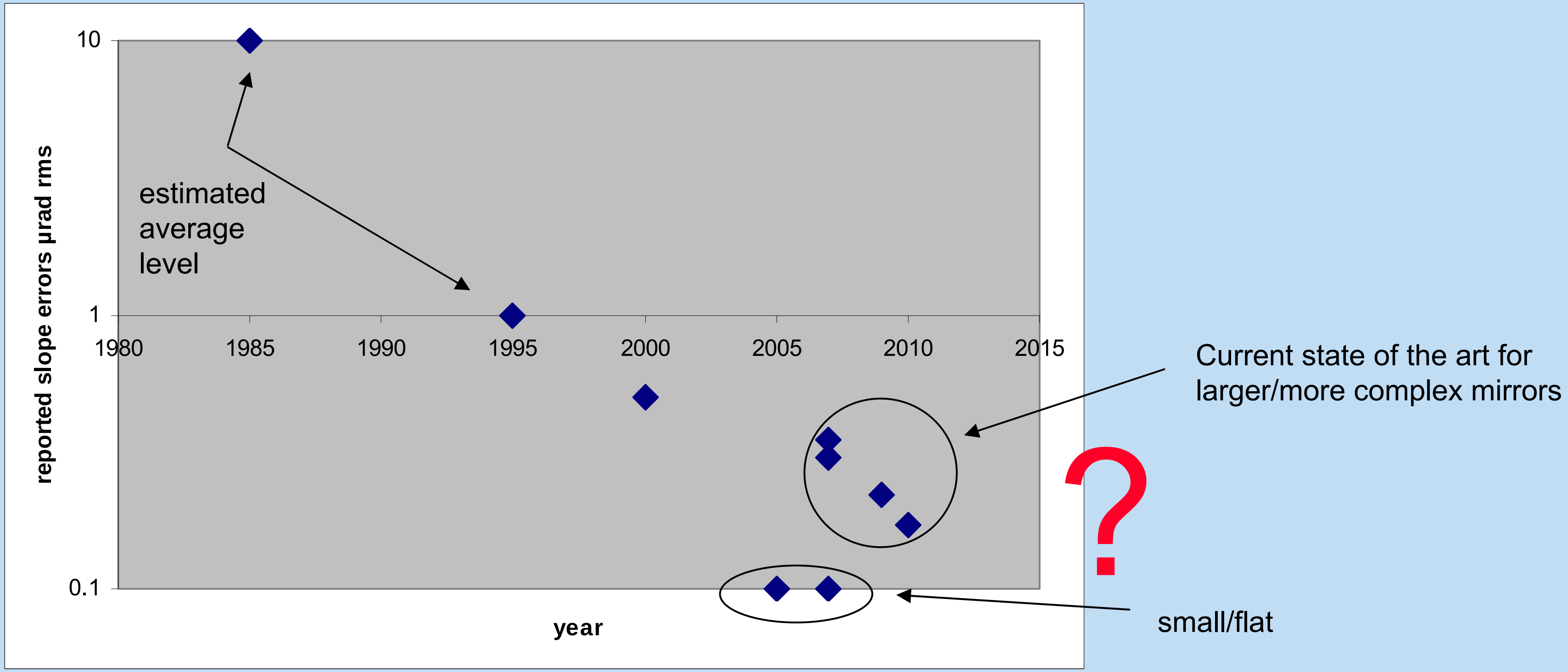
- Most profilers are operated at user facilities (mostly synchrotron optics labs)
- High-end profilers and interferometers are not easily commercially available
- Profilers are mostly used for verification, not for figuring
  - No absolute positioning and orientation data
  - Mirror edges/chamfers are 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



- 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 mirrrors

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	SiO2, 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 µrad	0.5 µrad 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.