ESRF OPTICAL METROLOGY APPLIED TO BENDABLE OPTICAL SURFACES

ACTOP08
Trieste Italy, October 9-11, 2008

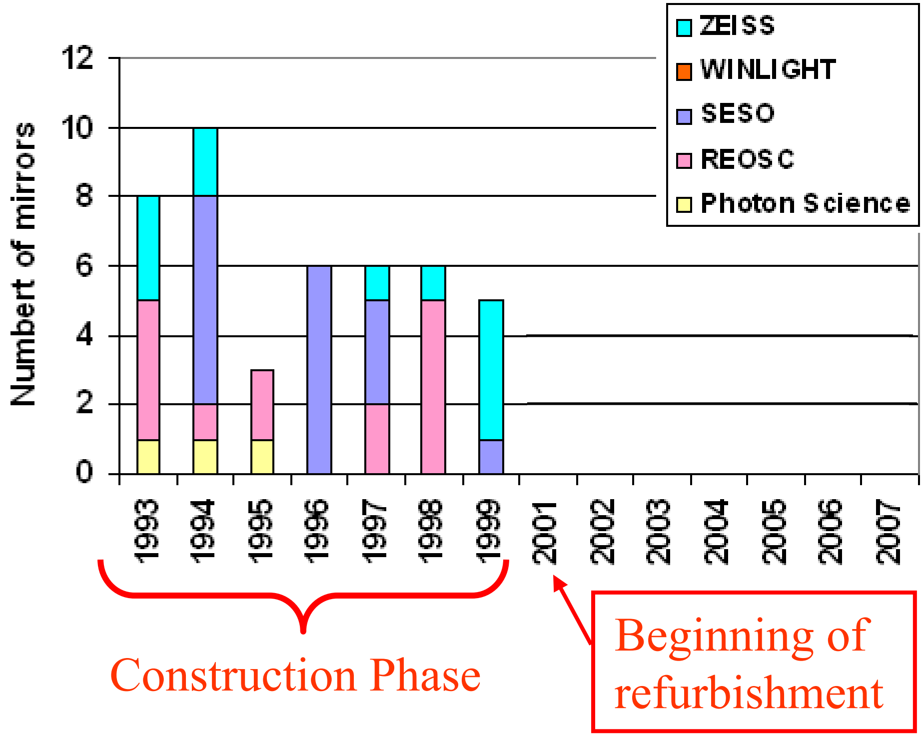
Amparo Rommeveaux

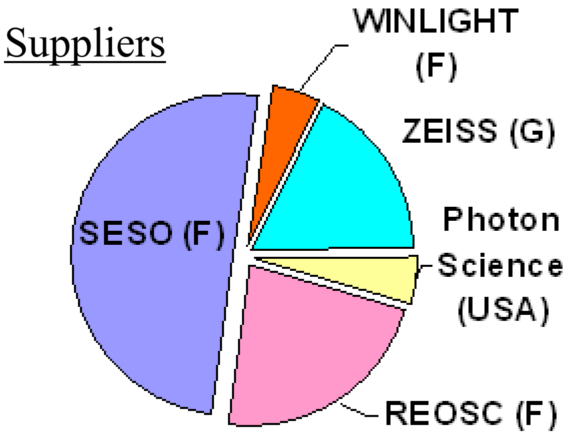
Raymond Barrett
Robert Baker

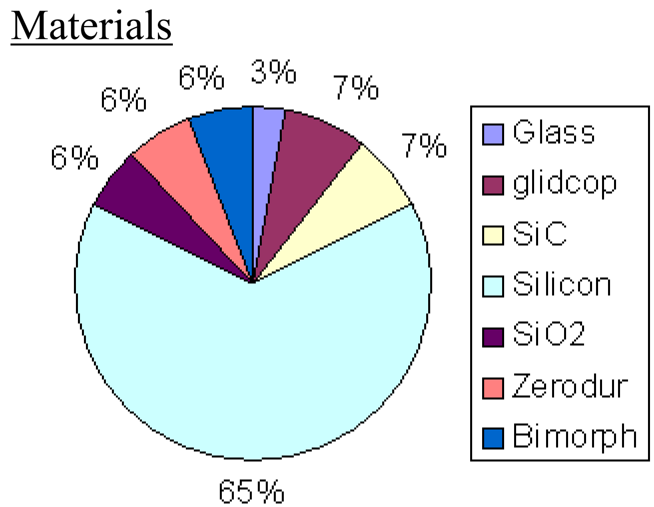
Outline

- Overview of 15 years of metrology at the ESRF
- ESRF small bender devices
- New LTP measurement procedures and calculation methods
- Last KB systems for Nano-focusing applications:
  - Bender technology
  - Fixed curvature mirrors
- Conclusion

ESRF Long mirrors : length ≥ 400 mm





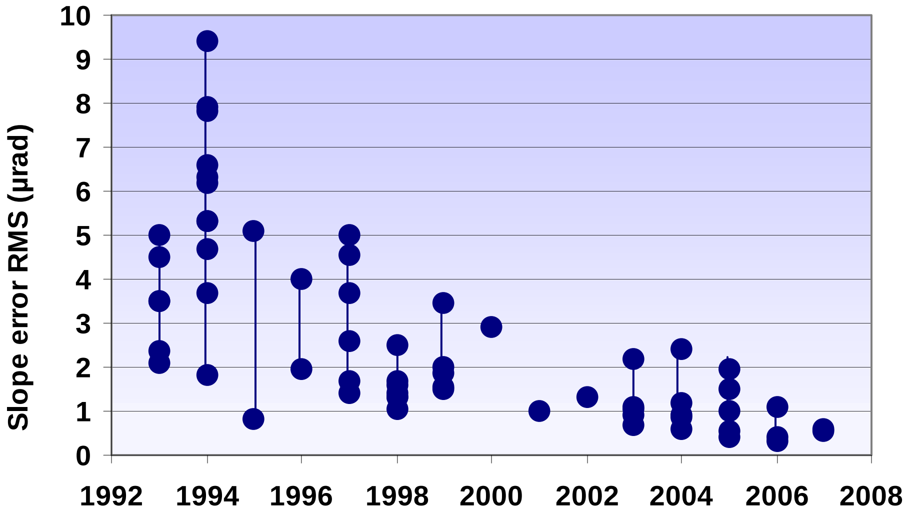


Metrology characterization of:

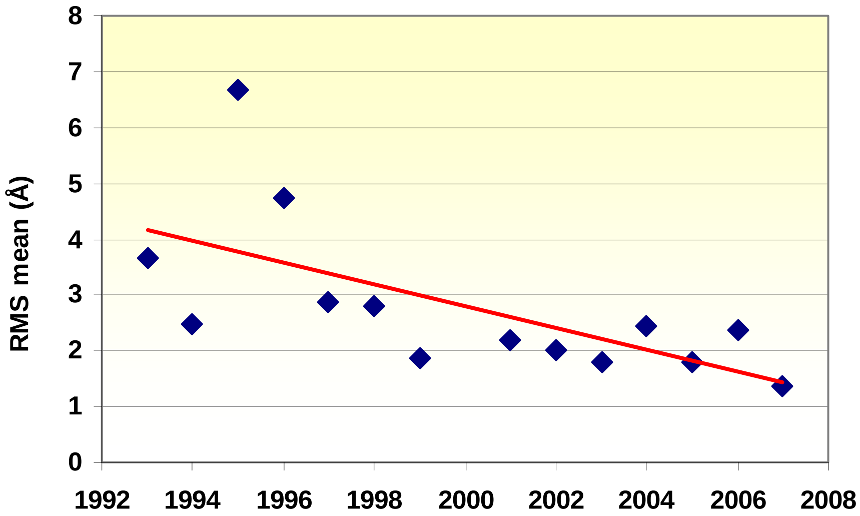
- 65 long mirrors (46 ≥ 700mm)
- 26 bending systems

ESRF Long Mirrors quality evolution

Slope errors
LTP



Micro-roughness
Wyko (10X) /Micromap (5X-50X)



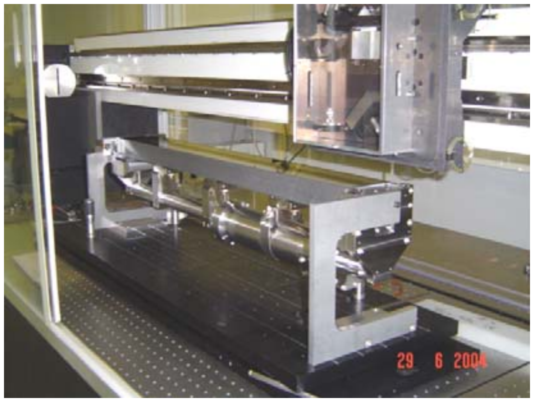
Best of slope error:

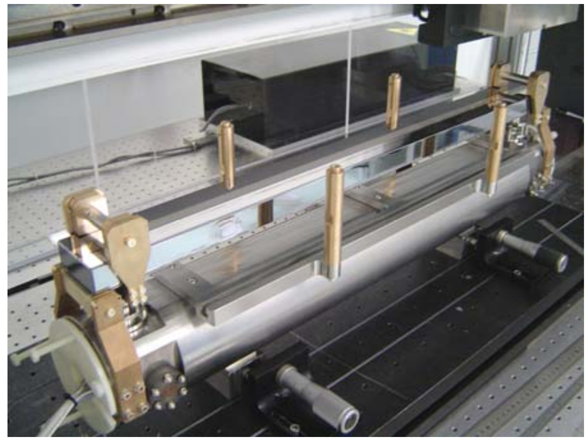
0.3 µrad / 900 mm - Silicon
Mirror size 1200x100x60 mm
but micro-roughness ≈ 3Å rms

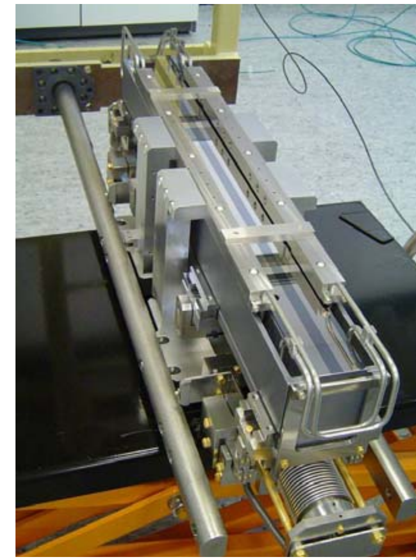
Best of micro-roughness:

0.6 Å - Silicon mirror
Mirror size 700x60x27 mm
but slope error ≈ 2 µrad rms

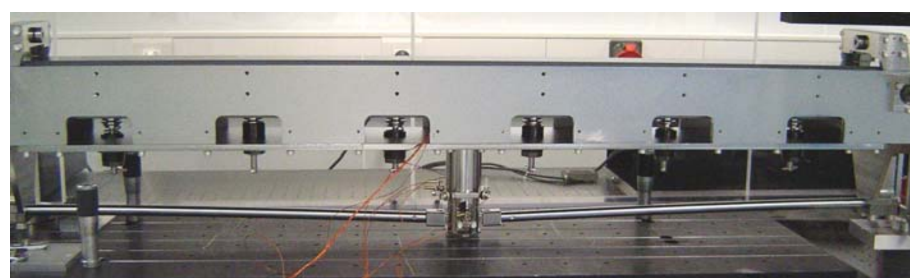
LTP characterization of Long mirror benders





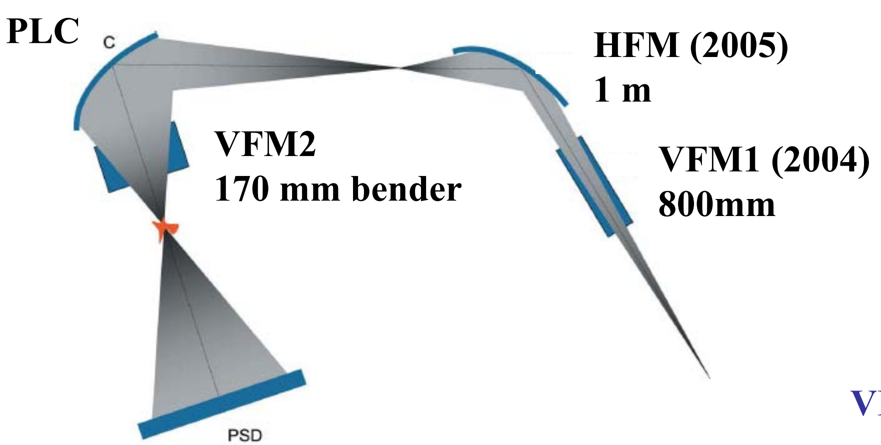


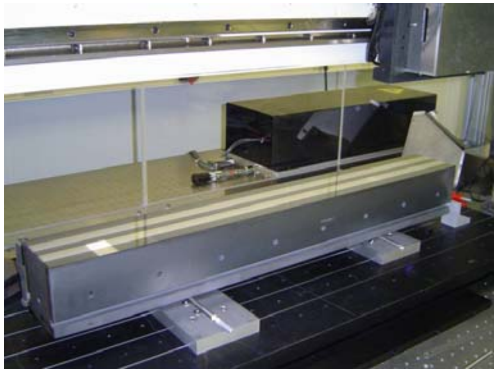
1. Mirror intrinsic slope error characterization (out of bender)
2. Mirror clamped on mechanics:
    - Evaluation of deformation induced by mechanics and correction if possible
    - Adjustment, optimization of gravity compensators
    - Verifying safety switches, range of curvature
3. Hysteresis cycles
4. Long term stability



Refurbishment: ID24 beamline

Energy dispersive/X-ray Absorption Spectroscopy (ED-XAS)

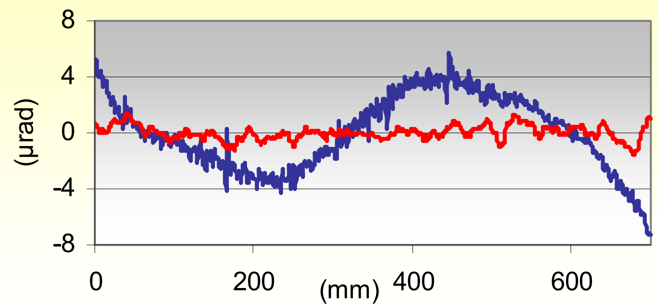




VFM1 (1995) :graphite +SiC- flat

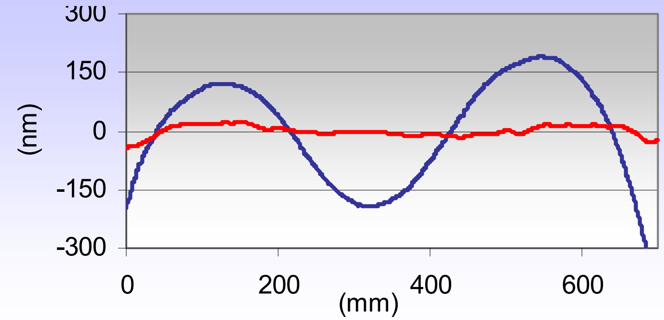
VFM1 (2004): Silicon - flat

Residual slopes to best sphere



1995 : 2.7 µrad rms
2004 : 0.5 µrad rms

Residual heights to best sphere

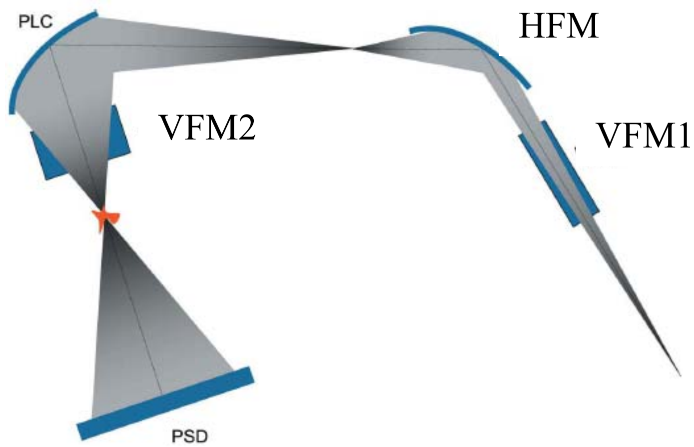


1995 : 137 nm rms
2004 : 14 nm rms

2005
HFM replacement:
flat mirror + bender
⬇
Elliptical mirror

Refurbishment: ID24 beamline

Energy dispersive/X-ray Absorption Spectroscopy (ED-XAS)

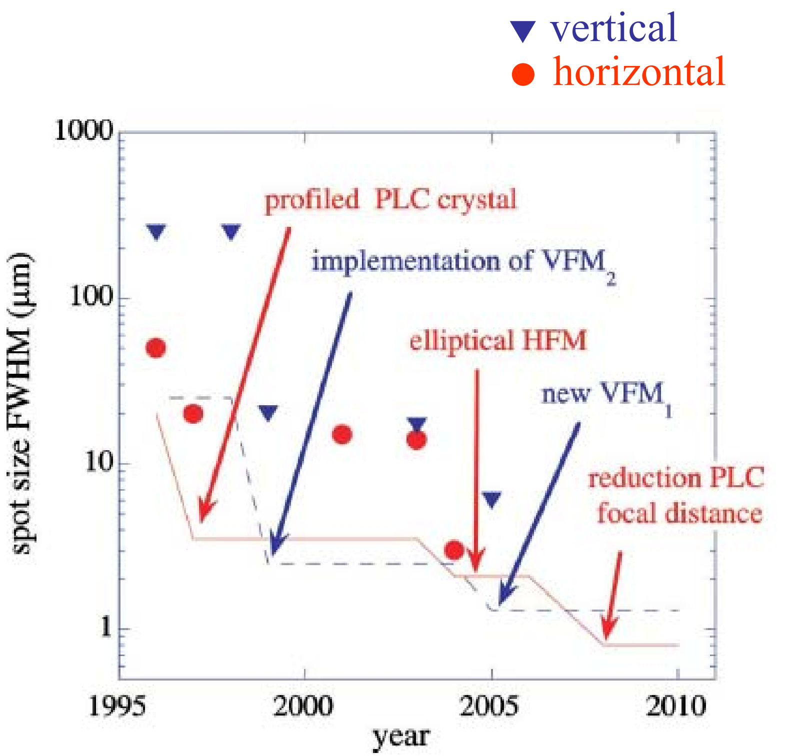


	Shape	Slope error (μrad) FWHM	*p* (m)	*q* (m)	*q*/*p*
VFM_1	Cylindrical	1.2	30	41	1.367
HFM	Elliptical	3.3	32.5	1.65	0.051
PLC	Elliptical	1.2	29.85	1.3	0.044
VFM_2	Elliptical	1.2	6	0.3	0.050

1995 : 50 μm x 110 μm

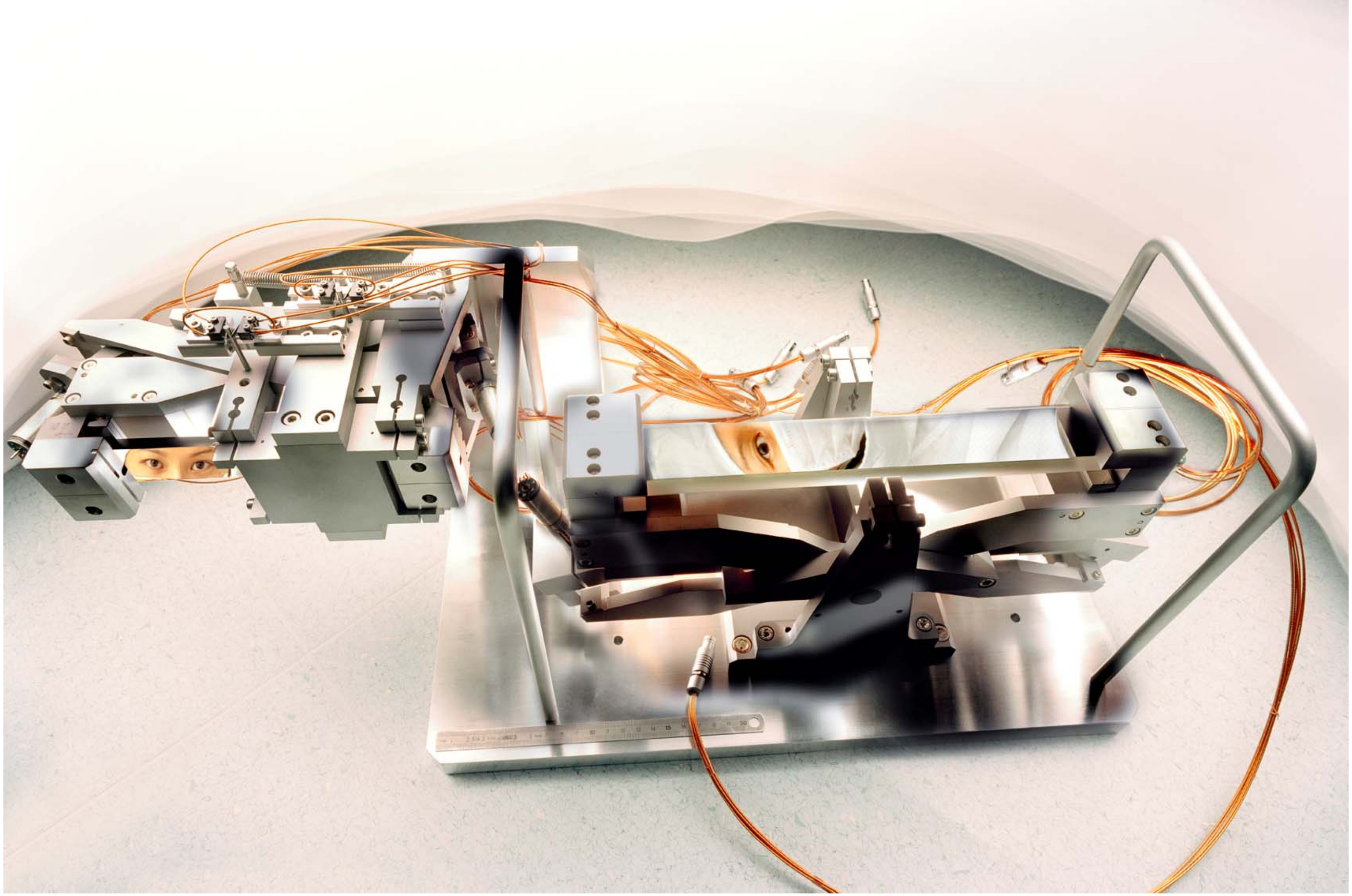
2006 : 2 μm x 5 μm

Significant spot size FWHM improvement !



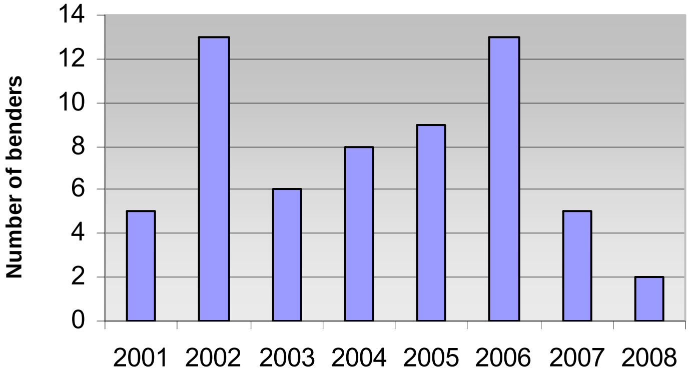
"Energy-dispersive absorption spectroscopy for hard-X-ray micro-XAS applications", S. Pascarelli et al., J. Synchrotron Rad. (2006). 13, 351–358

Kirkpatrick-Baez systems at ESRF

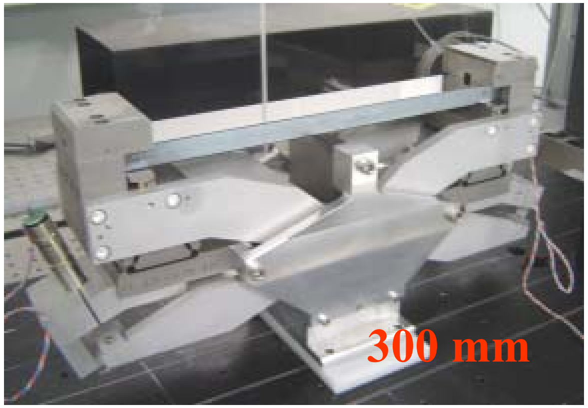


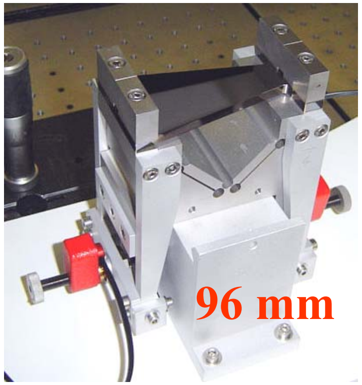
KB development at ESRF

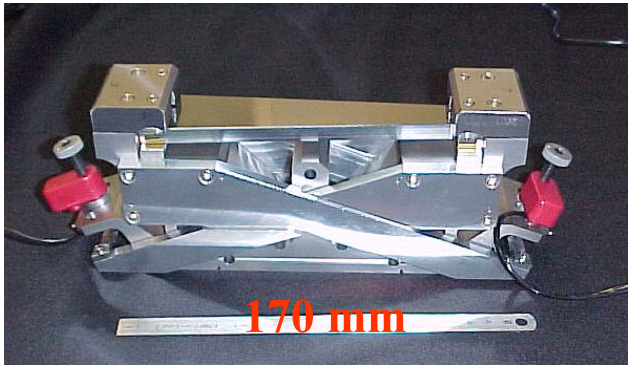
Since 2001: 61 benders tested and pre-shaped at the metrology lab
22 with multilayer coatings



Different configurations:
- Single bender (13)
- KB 170-170 (8)
- KB 170-96 (8)
- KB 170-300 (3)
- KB 300-300 (5)







Spot size

ID23	5 x 7 µm
ID27	2 x 4 µm
ID13	0.3 x 0.4 µm
ID22	76 x 84 nm
ID19	45 nm in Vertical Graded multilayer *

Spot size achieved is generally close to geometrical limit (i.e. not limited by optics aberrations)

* O.Hignette et al., AIP Conf Proc.- January 19, 2007 - Volume 879, pp. 792-795

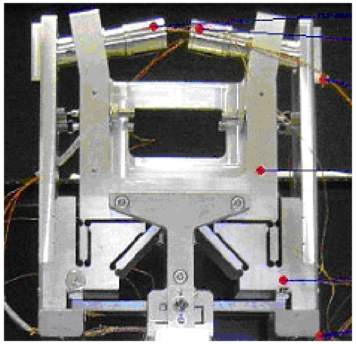
Metrology for thermal stability studies on KB

ID08 example: UHV bender

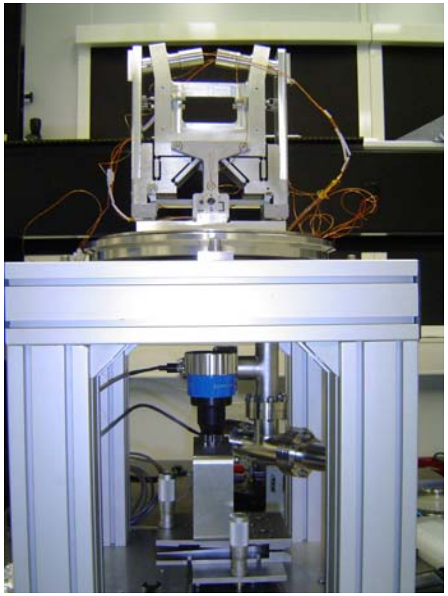
p=3 m
q=5 m } Rc =137 m
Θ= 28 mrad

Focused beam instability over 24 hours :
- spot position drift : >300 µm
- spot size increase: 70µm→500µm

Ex-situ evaluation of bender to determine origins of instabilities



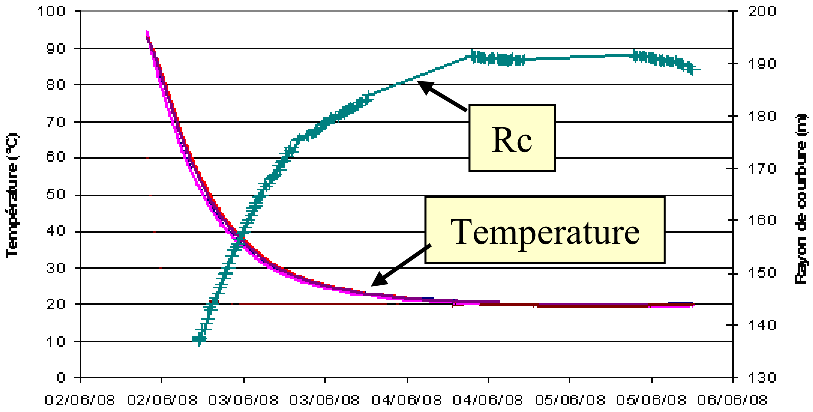
Software development for automated control of Fisba acquisitions



Setup with FISBA interferometer + 8 thermocouples

Setting high vacuum 2.10^{-8}mbar
6 days – baking up to 120° C

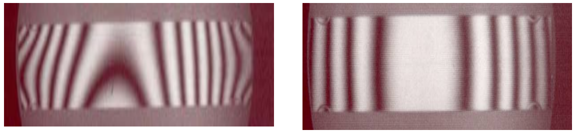
Monitoring Rc and temperature:
- 2.5 days to return to room temperature
- Mirror relaxing : 50 m (Rc=191m)



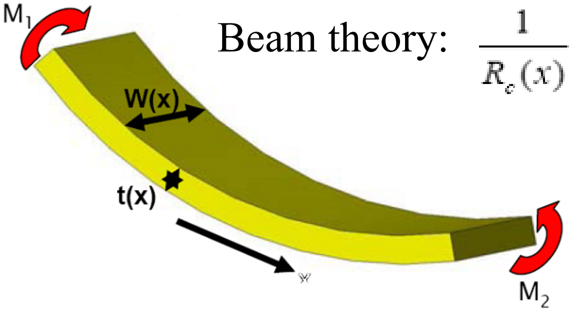
Time to reach stability defined

ESRF KB technology improvements

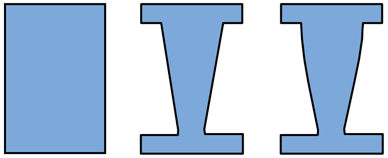
✓ Mirror clamping:
significant improvement of the interface mirror/mechanics



✓ Mirror width profile optimization mandatory for strong aspherizations

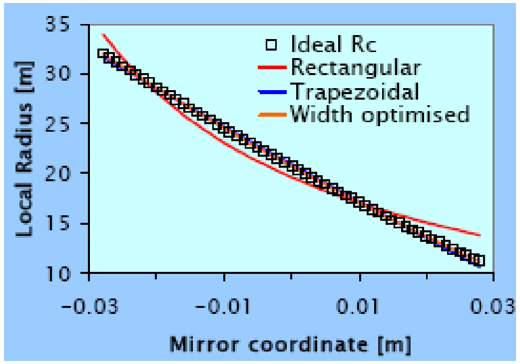


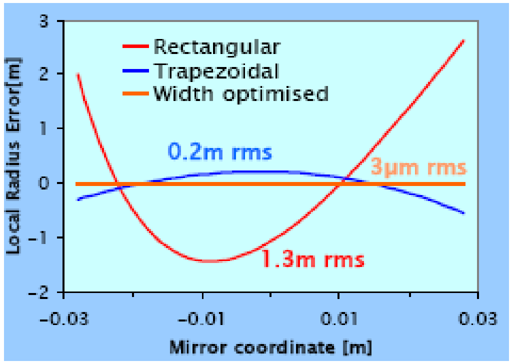
Beam theory: $\frac{1}{R_c(x)} = \frac{M(x)}{EI(x)}$ $I(x) = \frac{W(x)t^3(x)}{12}$ $R_c = \frac{2}{\sin\theta}\left(\frac{pq}{p+q}\right)$



$R_c(x)$ = radius of curvature
$I(x)$ = moment of inertia
E = Young's modulus
$W(x)$ = beam width
$t(x)$ = beam thickness

p=36 m
q=0.083 m
Θ= 8 mrad





Limitation: optimised for only one incidence angle

Quality highly dependent on optics

New generation of hard X-ray mirrors used in KB configuration:

- Short focal distance (tens of mm)
- Strong radius of curvature variation along meridian
- Shape error better than 1 nm P-V

Development of manufacturing techniques:

- Ion Beam Figuring (ZEISS, REOSC, ESRF…)
- Magneto-rheological finishing (SESO…)
- Differential coating (APS, Osaka University)
- Computer controlled optical surfacing (Tinsley Corp. …)
- Elastic Emission Machining (Osaka University- JTEC)

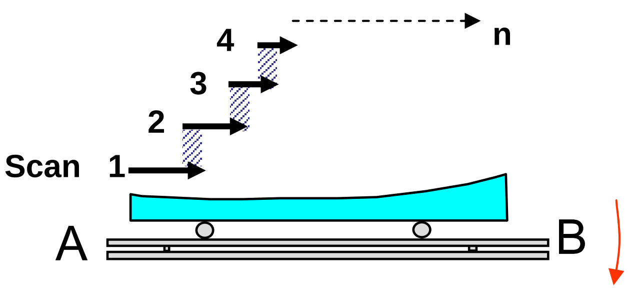
These techniques of deterministic surface correction require accurate metrology.

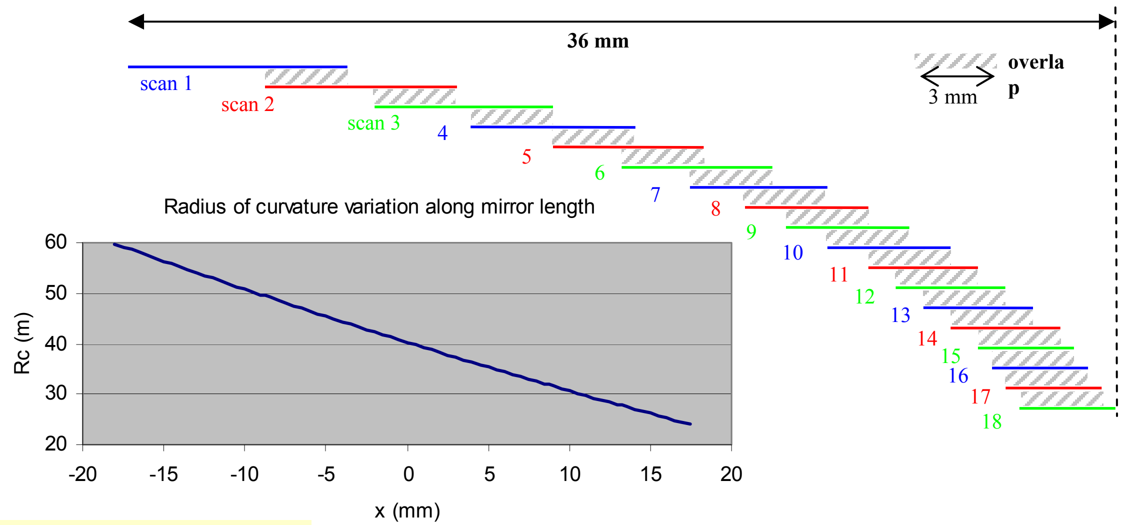
Measurement procedures : ESRF LTP stitching method

The idea is to split the scan line AB in short scans overlapped with:

1. small <u>and</u> constant angular deviation for each of them
2. constant spatial overlap

Before each scan, the mirror is tilted to reproduce similar LTP beam path over optical components.
Mirror slope profile is reconstructed by stitching all scans together.



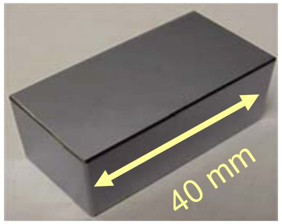


Reduction of LTP optics contribution

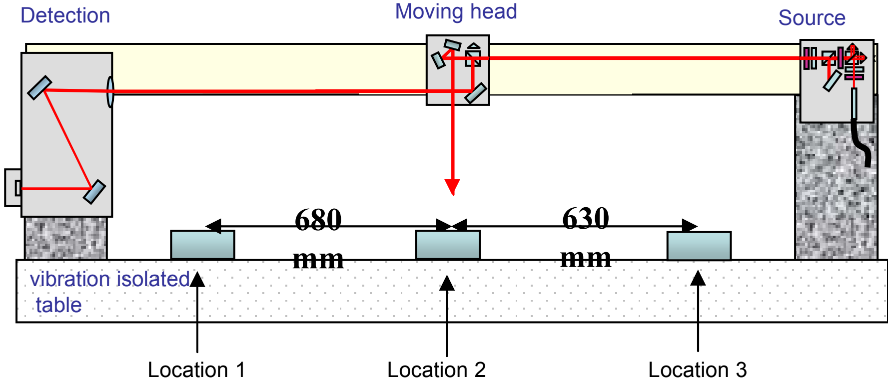
This procedure fully automated is quite fast

Illustration of ESRF LTP stitching results

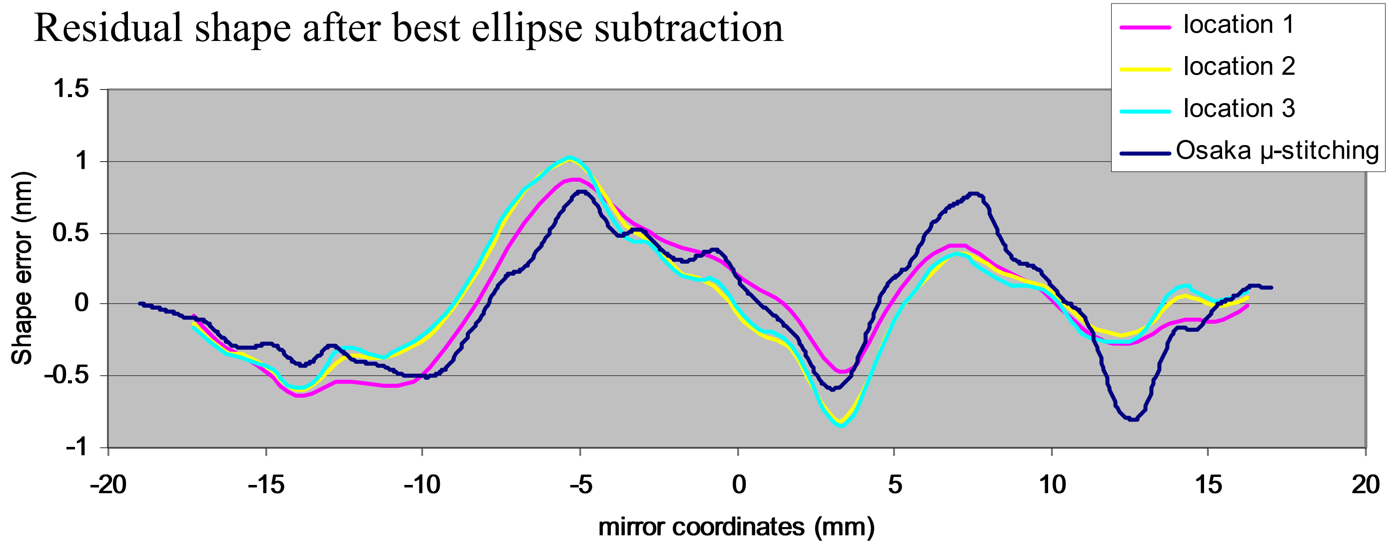
Mirror : SN1 provided by APS for the second 3big-RR
Design parameters: p=60 m, q=60 mm, θ=3 mrad



Slope error = 0.26 µrad rms
Shape error = 0.42 nm rms



Residual shape after best ellipse subtraction



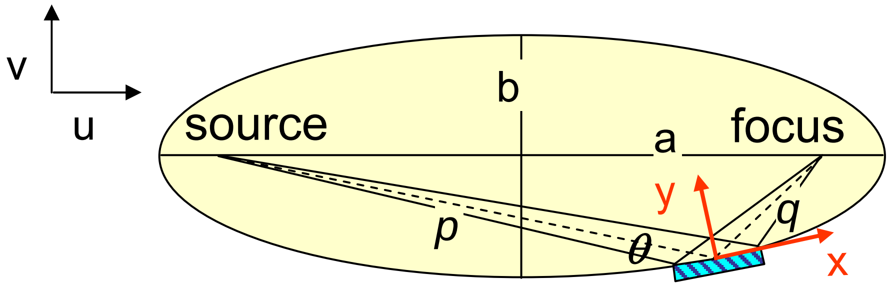
Agreement better than 0.5 nm peak to peak with micro-stitching interferometry result

Ellipse analytical description

Round-Robin on aspheric optics: APS/ SPring-8 / ESRF (SPIE Proc, vol. 6704, 2007)

Ellipse definition in the (u,v) coordinates system:

$$\frac{u^2}{a^2}+\frac{v^2}{b^2}=1$$



$$a=\frac{p+q}{2}$$

$$b=\sqrt{pq}\sin\theta$$

- p: Source distance
- q: Focus distance
- θ: Incidence angle

In the (x,y) coordinates system the equation of the ellipse figure is given by:

$$y(x)=-\cos\mu\times\left[\sqrt{b^2-b^2\times\left(\frac{x\cos\mu+x_0}{a}\right)^2}-y_0\right]+x\times\cos\mu\times\sin(-\mu)$$

x_0,y_0: coordinates of mirror center / ellipse center
μ: slope at the center of mirror in u,v coordinate system

Theoretical slope of ellipse is the derivative of ellipse figure equation

Optimization of **q** and **Θ** to minimize the RMS of residual slopes is necessary whereas slope errors are dominated by defocus !

Errors related to polynomial approximation

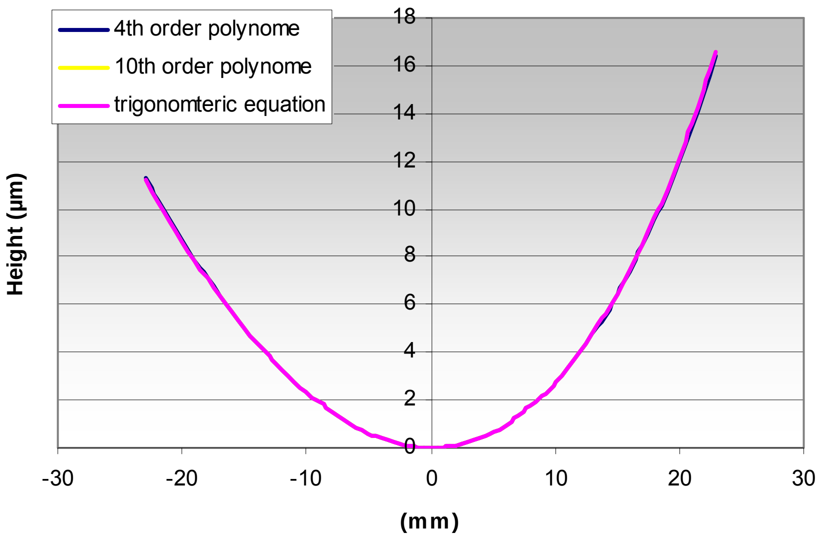
For large radius of curvature, approximation by a polynomial is acceptable
But not for strongly curved surfaces

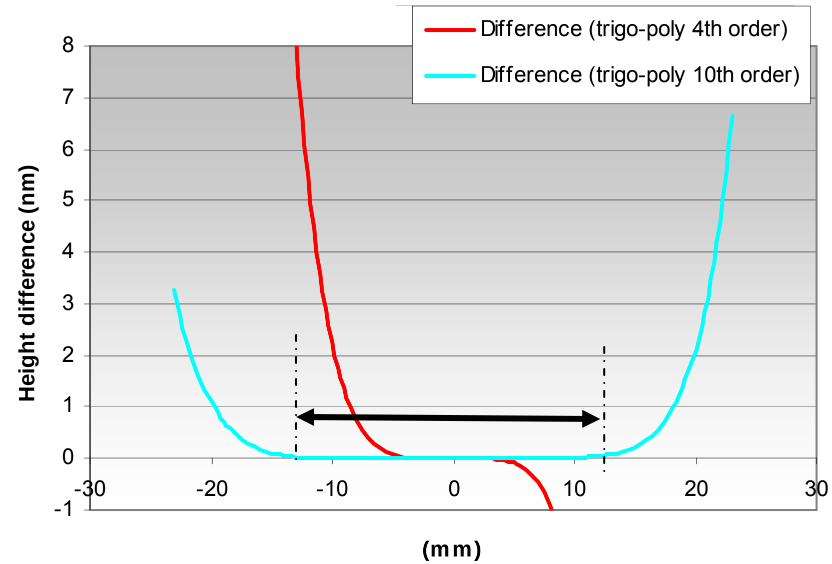
p=59.5 m
q=0.06 m
Θ=6 mrad

Rc ≈20 m

4th order:	**SUSINI**, "Design parameters for hard X-Ray mirrors: The European Synchrotron Radiation Facility case", Optical *Engineering* - Volume 34, Issue 2, pp. 361-376 (1995)
10th order:	**HOWELLS**, "Theory and practice of elliptically bent X-ray mirrors", *Optical Engineering* - Volume 39, No10, pp. 2748-2762 (2000)

Theoretical ellipse profiles

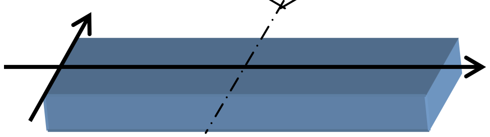




4th order : valid on 20% of length
10th order: valid on 50% of length

Precision required on mirror coordinates

- Center of mirror definition: LTP encoder + fringe pattern detection repeatability achieved ± 6 microns



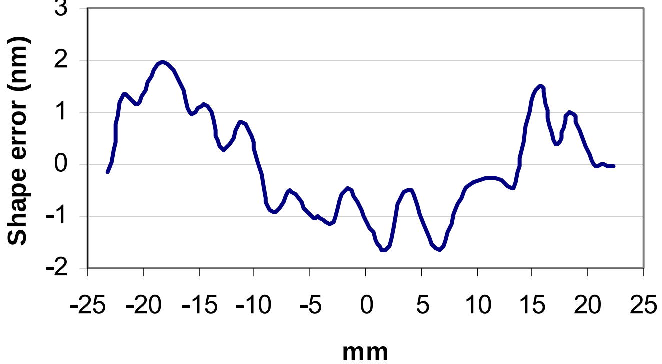
Mirror coordinates are equally interleaved
Values are rounded to a tenth of mm
(can get better with encoder feedback but not used up to now!)

What is the consequence of an uncertainty in the determination of X mirror coordinates of the order of a tenth of a micron ?

Numerical example :

p=59.5 m
q=0.06 m
Θ=6 mrad

} Rc ≈20 m



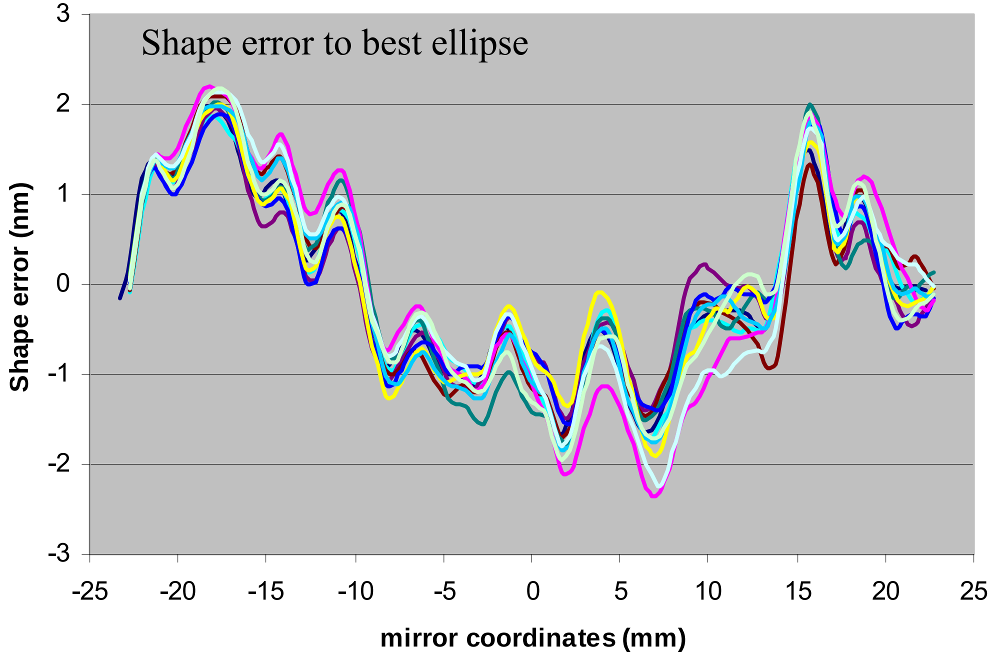
Starting from an LTP measurement with a sampling step of 0.5 mm

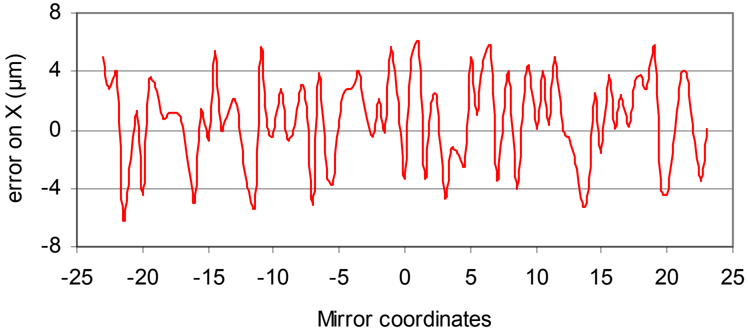
- X position array rounded to tenth of mm
- Slope array

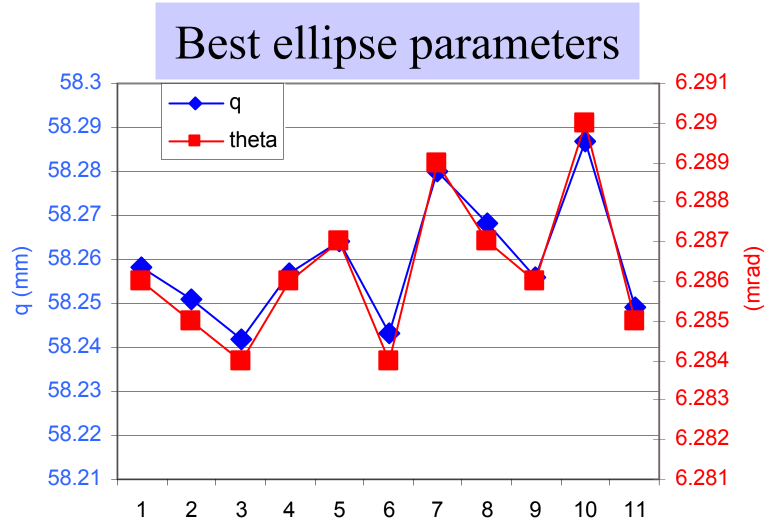
Now, random noise is added to mirror coordinates array

Precision required on mirror coordinates

Random noise added to mirror coordinates array
amplitude ± 6 microns
Applied 10 times







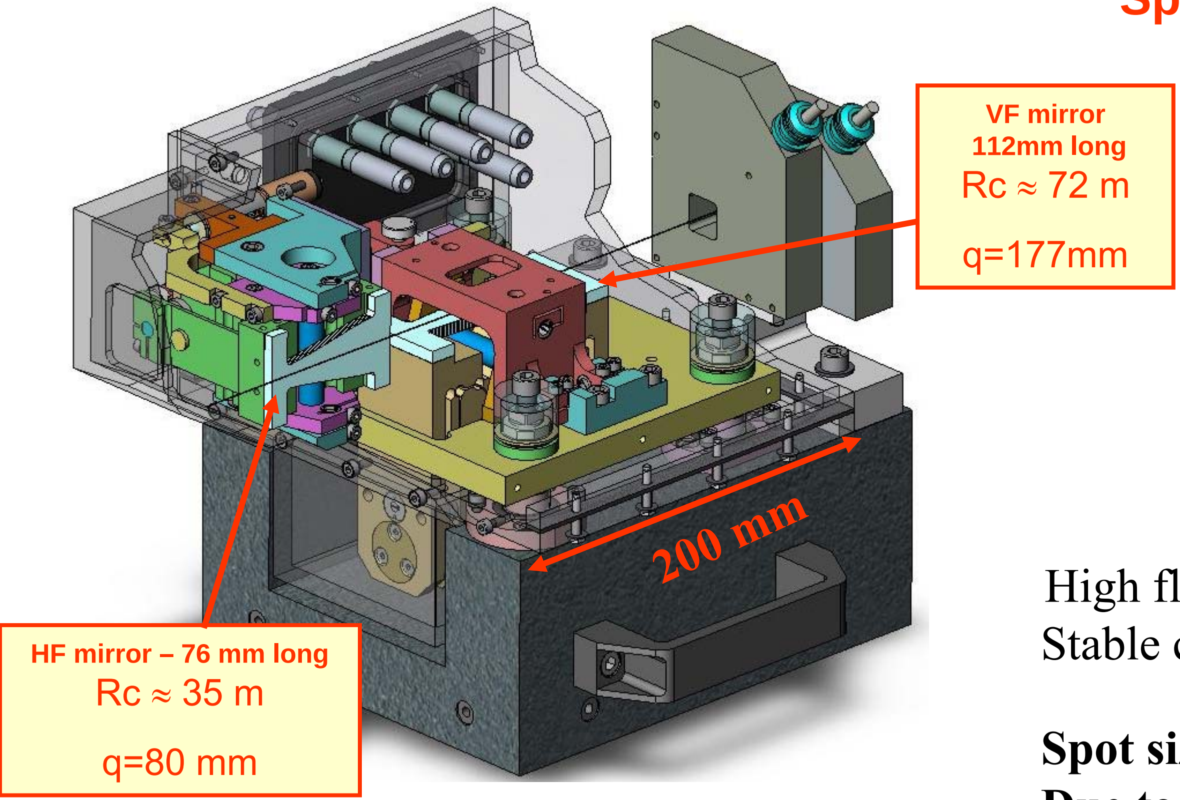
Discrepancy: up to 1 nanometer peak to peak !

focal distance : 45µm
Incidence angle : 6 µrad
Ratio p/q = constant

Nano-focusing: ESRF 'state of the art' KB system

Compact Dynamic KB
ID13 Microfocus

Spot size goal : 200nm x 200nm



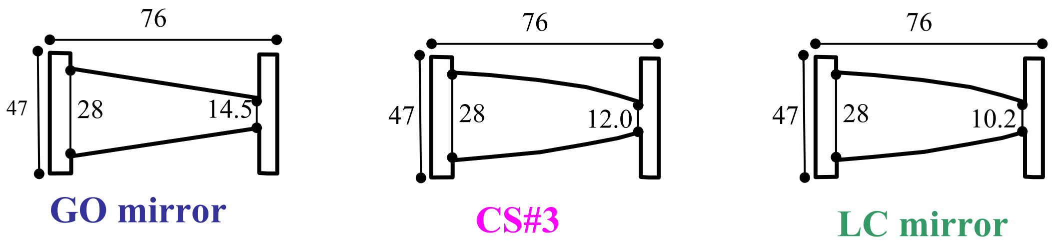
- Flex arm bender design
- Width profiled mirrors
  VF Shape error rms : 3.2 nm rms
  HF Shape error rms : 6.9 nm rms
- Bonding optics technology
- All invar construction
- Online orthogonality adjustment

High flux measured : 10^{11}photons
Stable curvature over several days

Spot size achieved : 300nm x 250nm
Due to non-optimal mirror profile…

Compact Dynamic KB : Mirror profile width influence

Horizontal Focusing Mirror : 3 different width profile tested

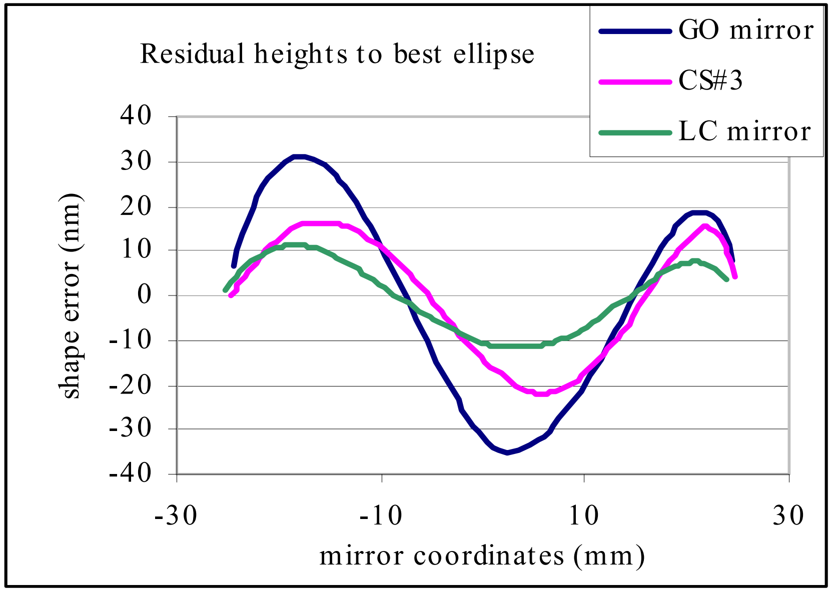


Ellipse parameters:
p =98m, q=80mm and θ=4.4 mrad

scan length (mm)	slope error rms / best ellipse	shape error rms / best ellipse
50 mm	1.4 µrad	6.9 nm
40 mm	0.35 µrad	1.4 nm

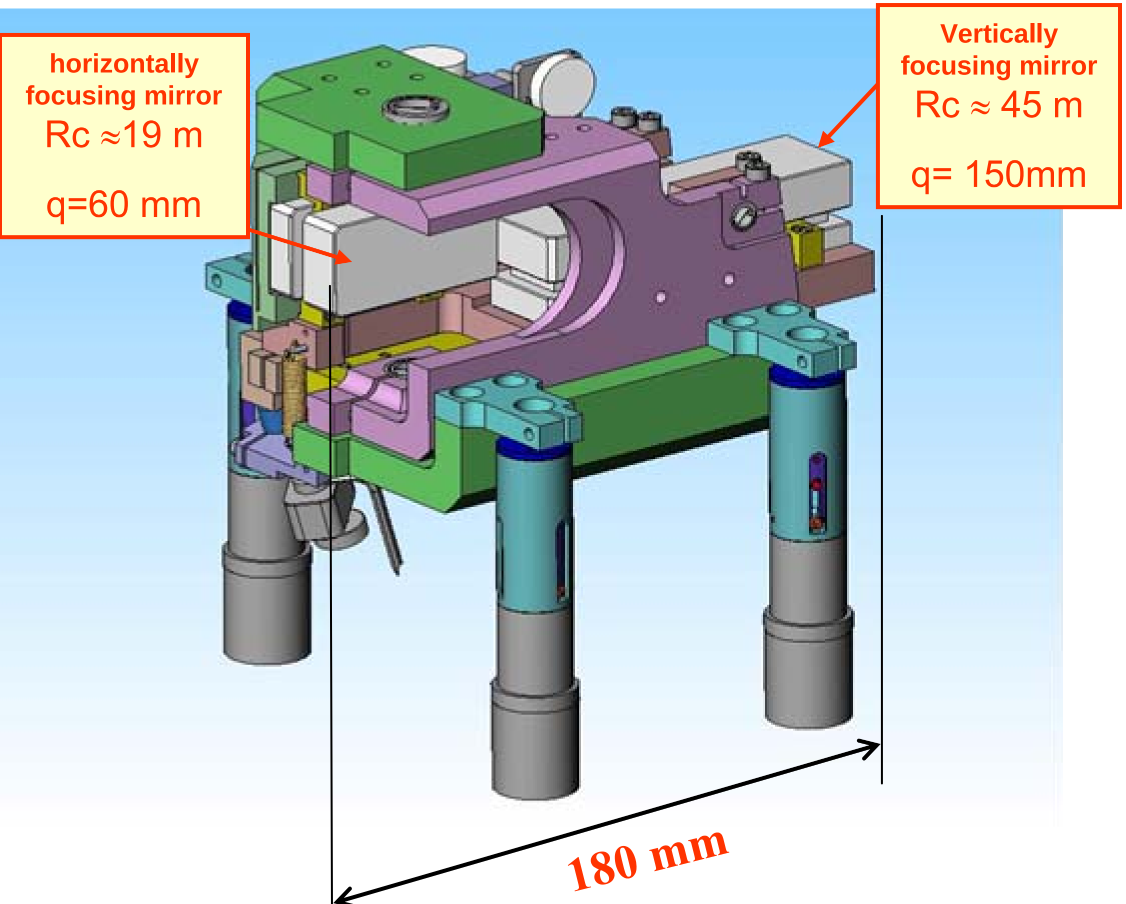
Optimal width not achieved:

- manufacturing errors ?
- bad model ?



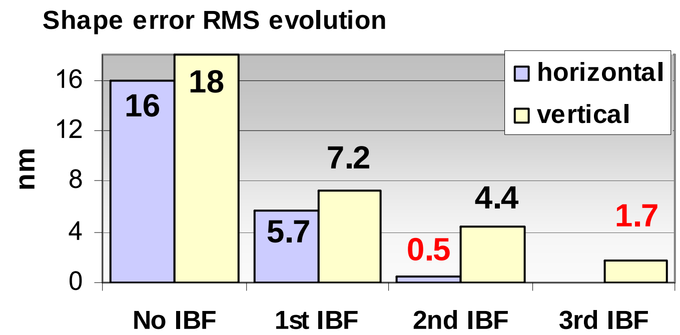
Nano-focusing: ESRF 'state of the art' KB system

Compact fixed curvature KB
ID21 X-ray Microscopy



Spot size goal : 200nm x 200nm

- 110mm / 60mm IBF optics (ZEISS)
- 2/3 IBF iterations: roughness < 3Å



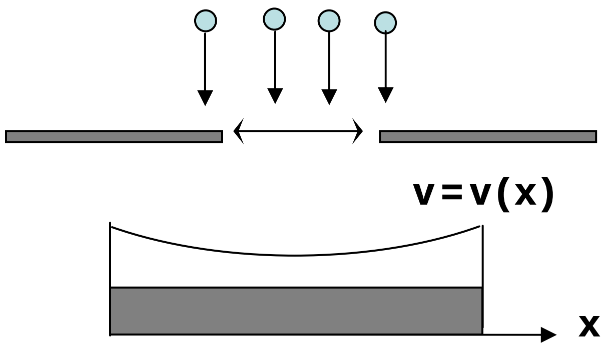
- All invar construction
- UHV Picomotors
- Invar body capacitive sensors

Ion Beam Figuring at ESRF

Approach # 1: direct surfacing

Gap **scans**

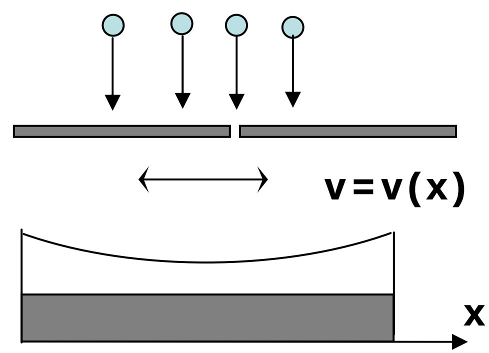
2 blades - online metrology absent

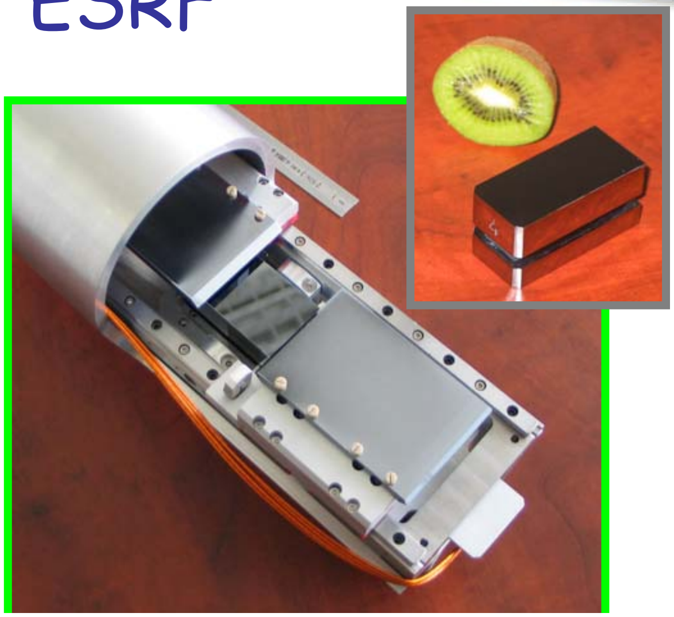


Approach # 2: figure correction

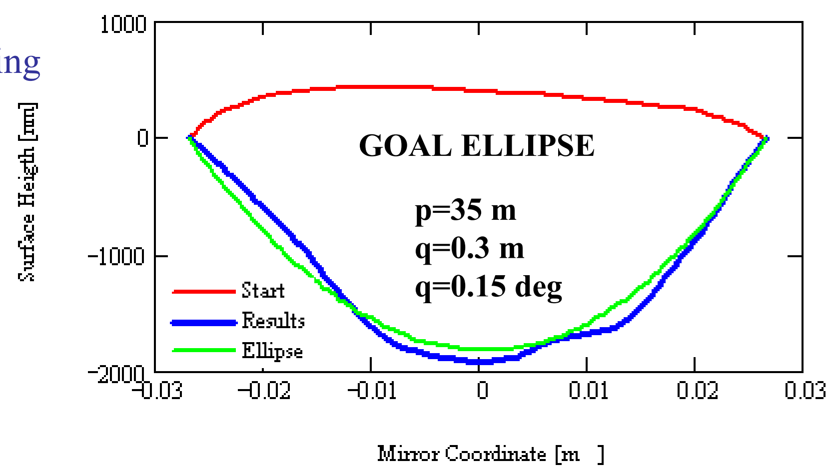
Offset scans

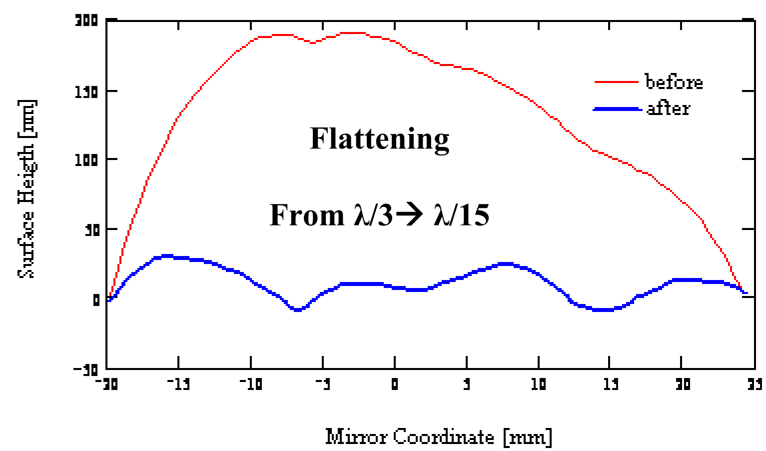
2 blades - online metrology





Direct surfacing results





Good Shape but slope errors still too high (~30μrad)

Summary

- Long mirror optical surface quality has been really improved over 15 years
- Micro-roughness still limited above 1Å rms for flat mirrors and higher values for cylinders

- Today, KB development at ESRF is oriented towards nano-focusing needs with particular emphasis on stability issues.
- Due to compacity criteria, new approaches of KB are investigated:
  - bonded technology in dynamic KB
  - fixed curvature mirrors prefigured by IBF or differential coating (APS-ESRF)
- Optical metrology has also been improved:
  - development of LTP measurement procedures
  - Round-Robin activity
- Metrology plays a key role in all these developments.

Acknowledgements

- L. Assoufid (APS, USA) and H. Ohashi (SPring-8, Japan)
- Sakura Pascarelli (ESRF)
- Manfred Burghammer (ESRF)
- Luca Peverini (ESRF)
- Francois Perrin and Pierre Bondois (ESRF)

Thank you for your attention !