# Focusing X-ray beams below 50 nm using bent multilayers

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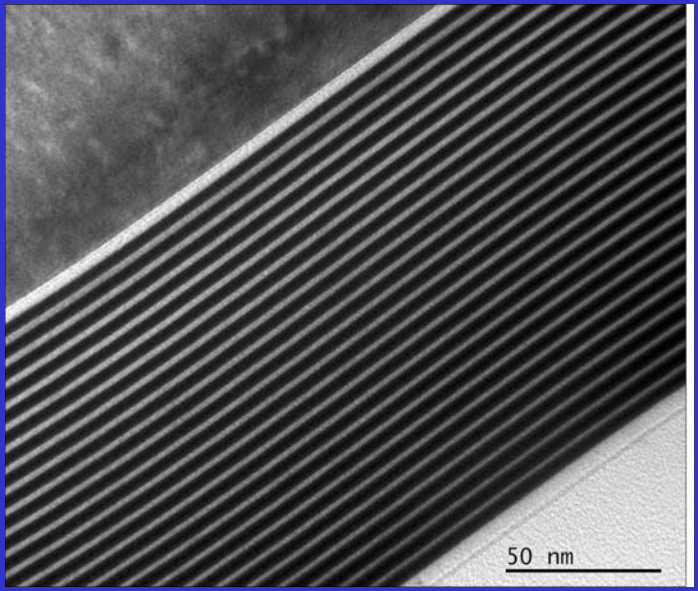
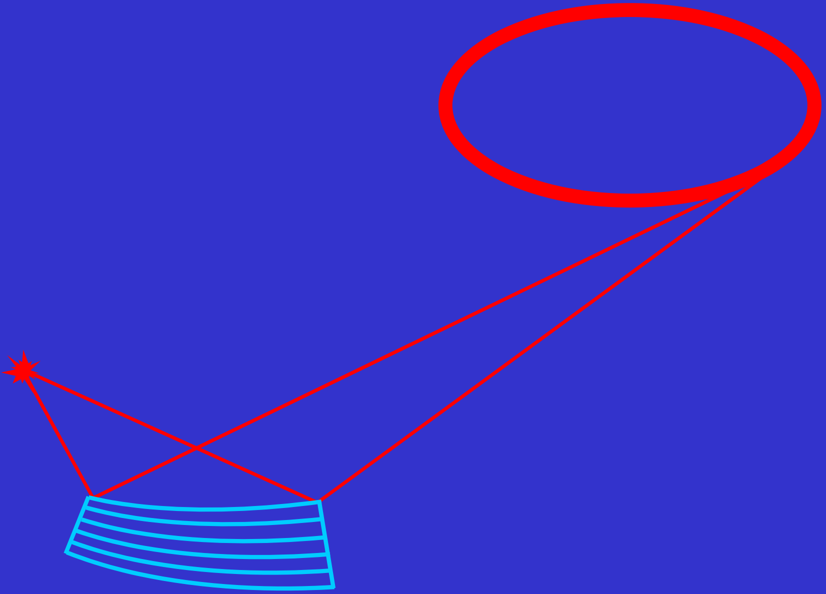
*European Synchrotron Radiation Facility (FRANCE)*

## Outline

- Graded multilayers  resolution limits
- 40 nanometers focusing
- Fabrication and metrology processes
- projection microscopy
- Perspectives

# graded multilayer resolution limits





diffraction limited
full width half maximum

$$\mathrm{FWHM} = 0.44 \frac{\lambda}{NA_{max}} \cong \frac{1.7\,\Lambda\,f}{L}$$

Energy independant

Λ d-spacing
λ Wavelength
f focal length
L mirror length
NA numerical aperture

Ultimate FHWM ≅ 4 nm

**Are volume diffraction – scattering effects limiting factors ?**

# Multilayer comparison with metal coated mirrors

Metallic mirror width limit

For Platinum FWHM = 21 nm

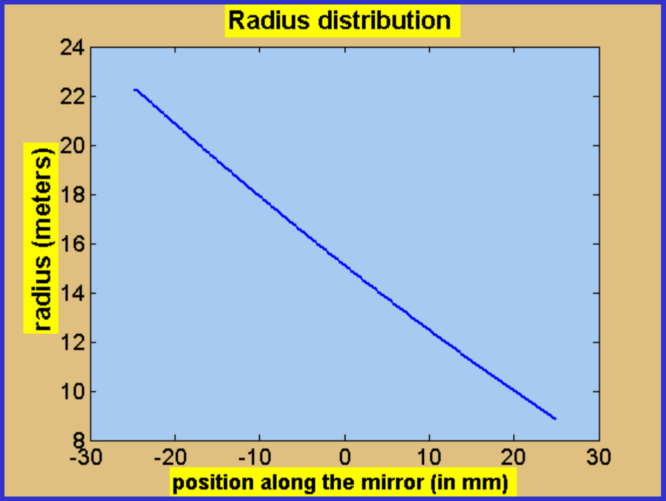
$$\boxed{\mathrm{FWHM} = 0.44\frac{\lambda}{\mathrm{NAmax}} \cong \frac{1.3\lambda}{\theta_c}}$$

$$\boxed{\boldsymbol{\lambda = 2\,\Lambda\sin\theta}}$$

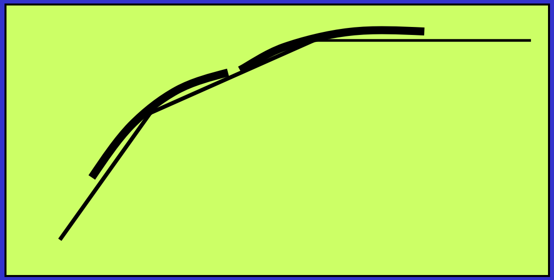
angle of incidence 5X larger than Pt
for 20 Angstrom d-spacing

Small focal length with large acceptance possible

High energy applications

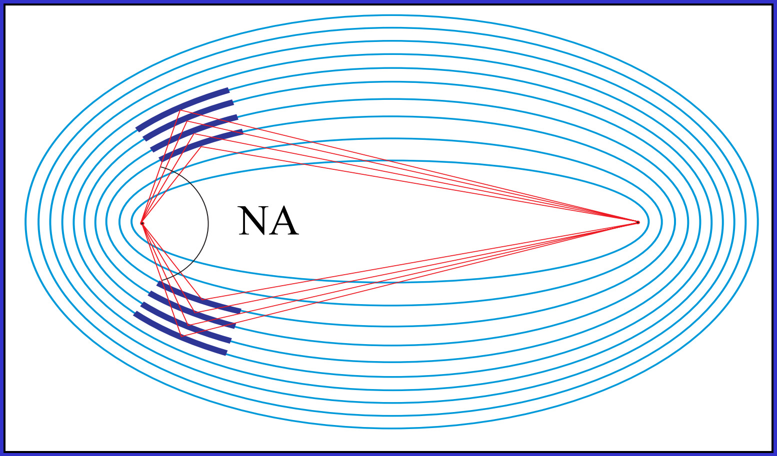


# Pushing the limits : double reflections and annular type architectures



**4 mirrors KB**

**NA$_{MAX}$ X 2 FWHM ≅ 2 nm**



Ellipsoid NA ≅ 2θ

**NA$_{MAX}$ X 4 FWHM ≅ 1 nm**

Wolter II **NA$_{MAX}$ X 8 FWHM ≅ 0 .5 nm**

# Limiting factors

Alignment ,vibrations, T drifts

mirror figure errors and roughness

Multilayer fabrication inaccuracies

Volume effects (evanescent wave, phase shifts, scattering)

## Diffraction limited figure  tolerances

$$\boxed{\sigma_z = \frac{\lambda}{27 \sin\theta} = \frac{\Lambda}{13.5}}$$

$\Lambda$ multilayer d-spacing

$\lambda$ Wavelength

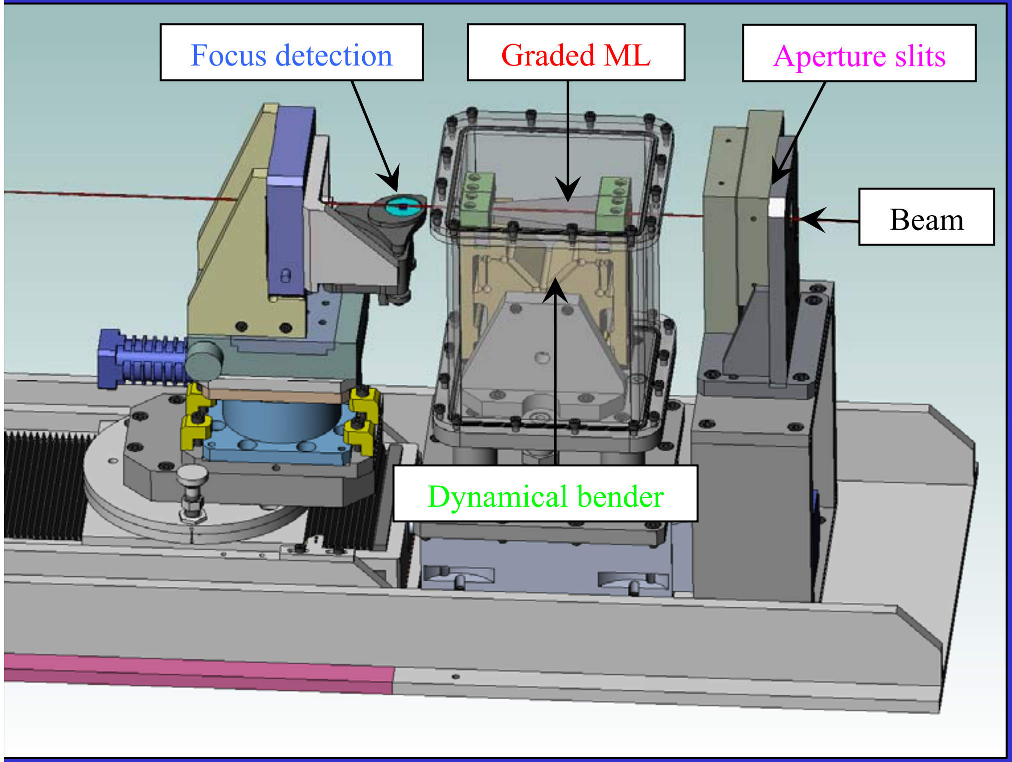
$\theta$ incidence angle

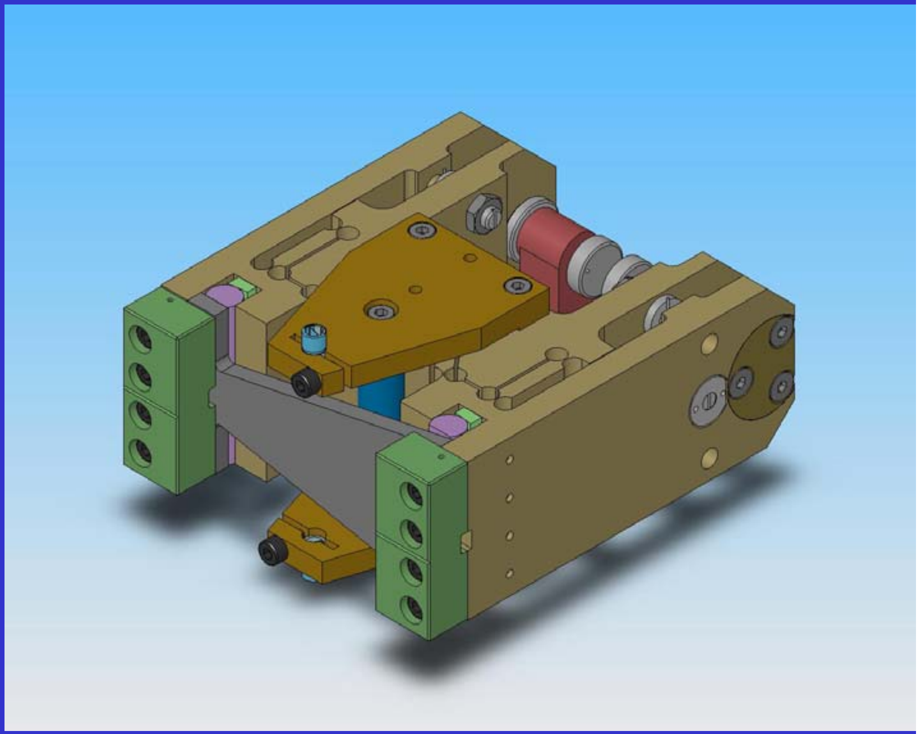
$\sigma_z$= 0.22 nm rms for $\Lambda$=3 nm

$\sigma_z$= 0.8 nm rms for Platinum

sub-angstrom roughness for multilayers

# ID19 line nanofocusing multilayer experiment





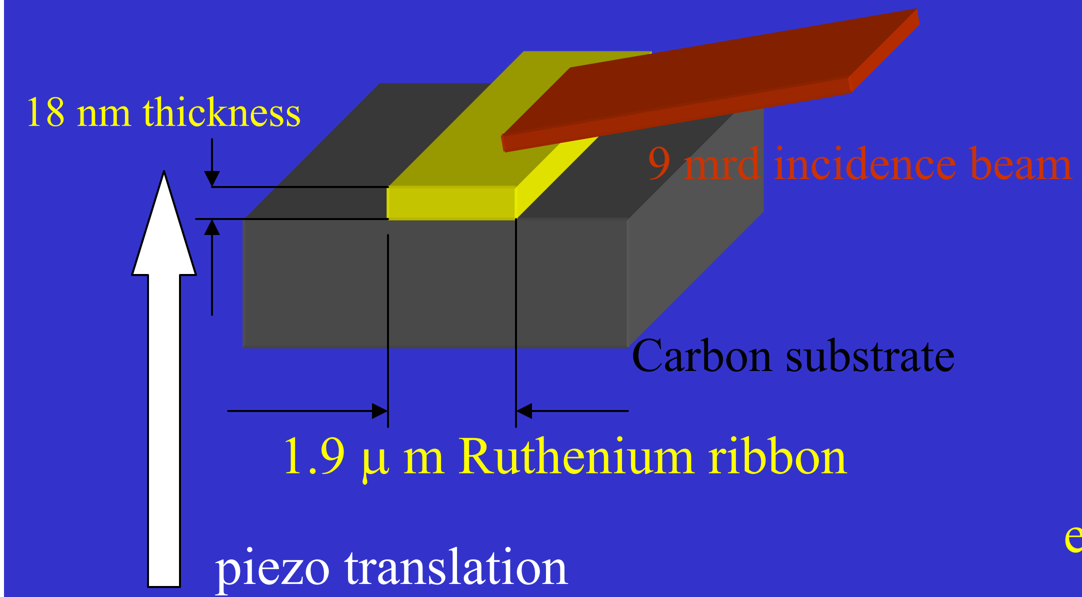
Mirror bender

$[W/B_4C]_{25}$

Energy 24 Kev
focal length 80mm
incidence angle 5.5 mrd
vertical 25 µm FWHM source at 150 m

$\frac{\Delta E}{E} = 6\%$

# Nanowire fluorescence linewidth measurement



18 nm thickness

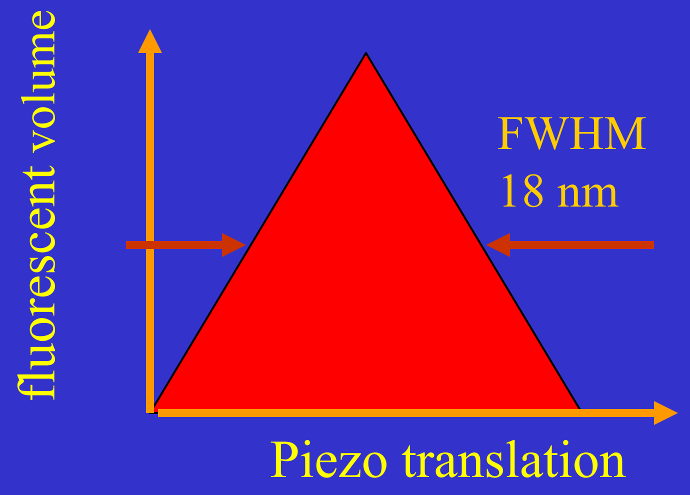
9 mrd incidence beam

Carbon substrate

1.9 µ m Ruthenium ribbon

piezo translation

equivallent fluo-nanowire function



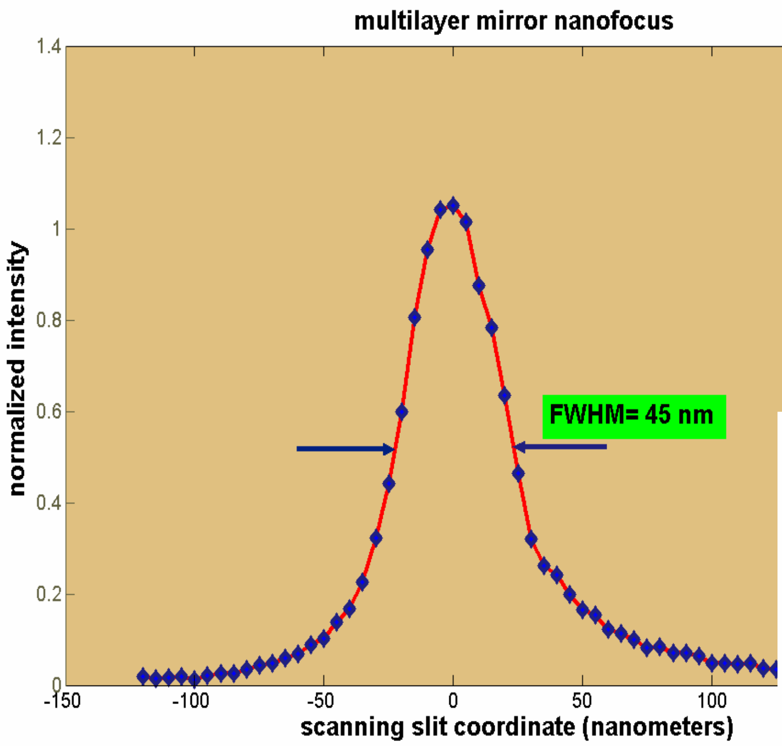
fluorescent volume

FWHM
18 nm

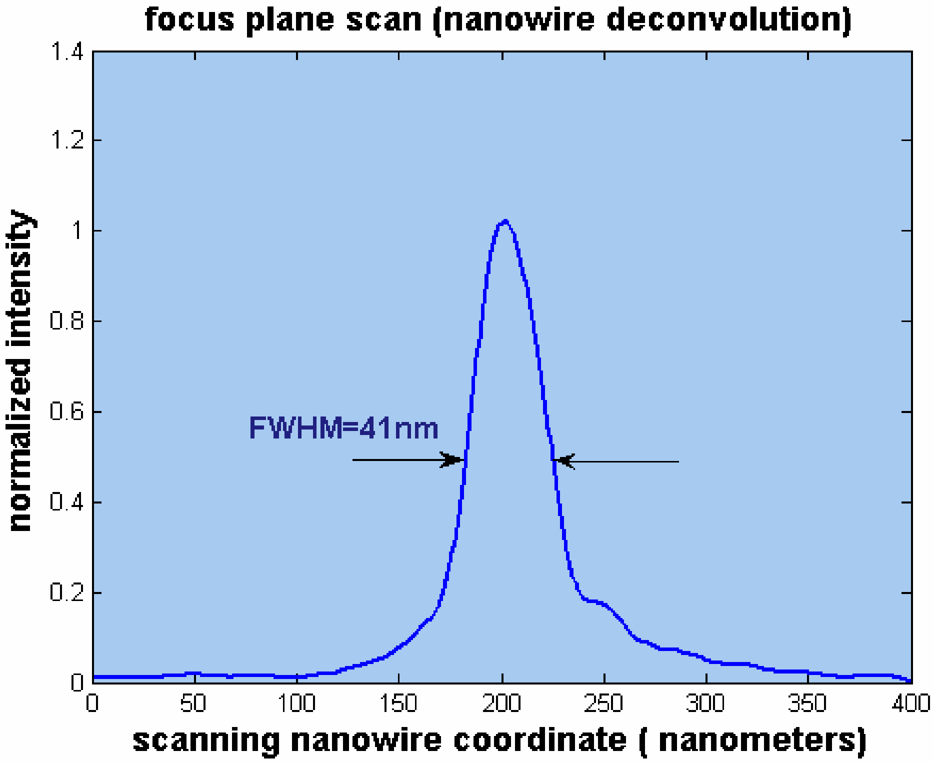
Piezo translation

# Line profile measurements

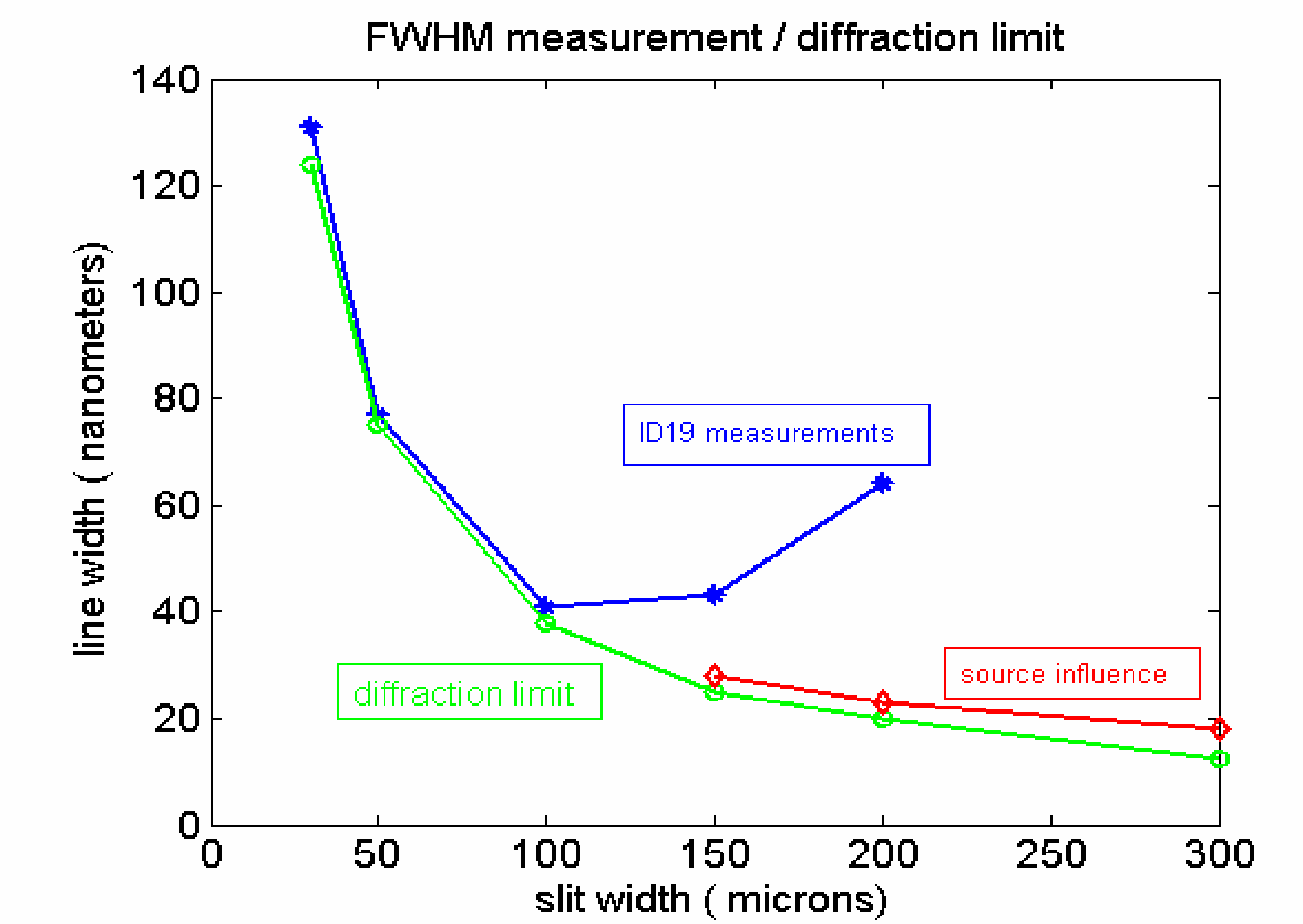
## Raw data


multilayer mirror nanofocus

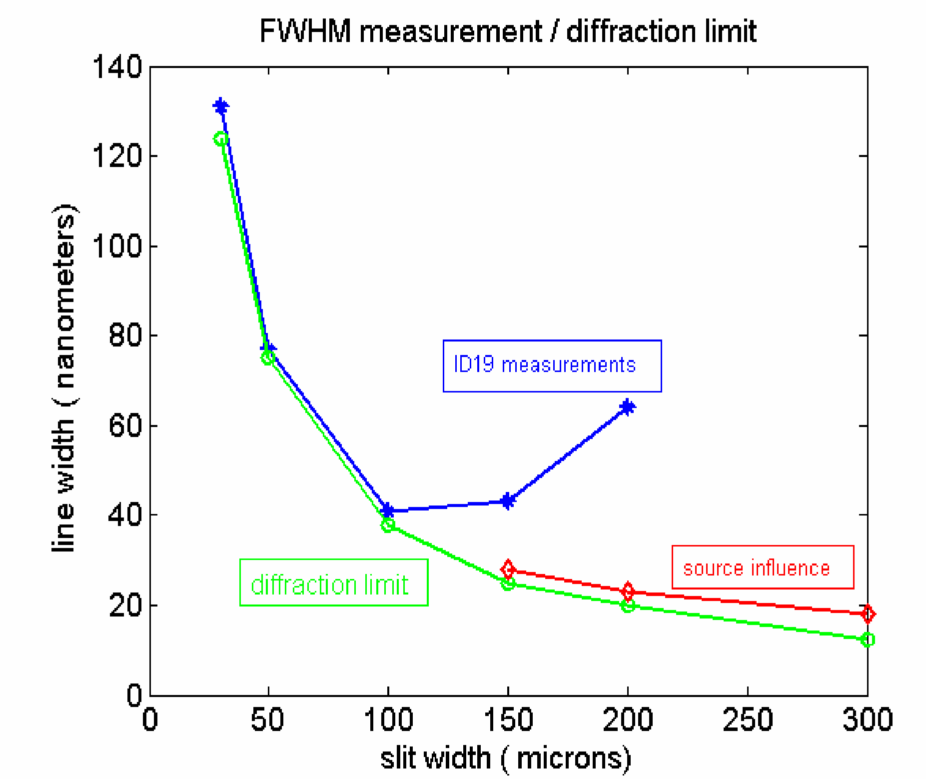
nanowire volume deconvolution


focus plane scan (nanowire deconvolution)

# Linesize versus acceptance

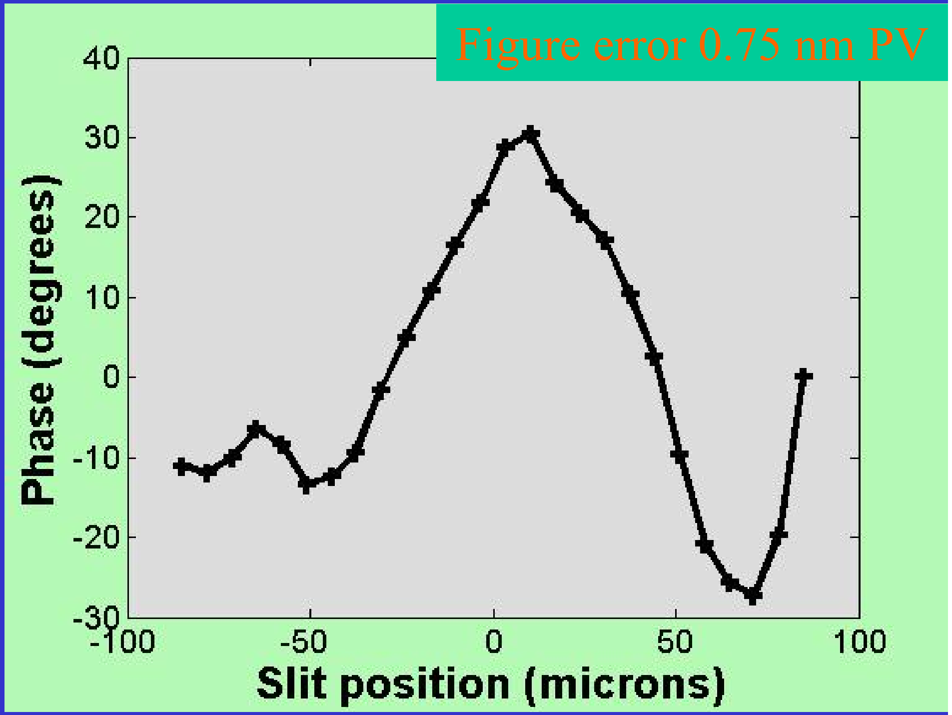


# Mirror figure errors limitations ?



line size vs acceptance

Wavefront phase error
From Xray in situ metrology



Estimated error 25 nrd rms
(Pencil beam method )

# Vibrations measurements

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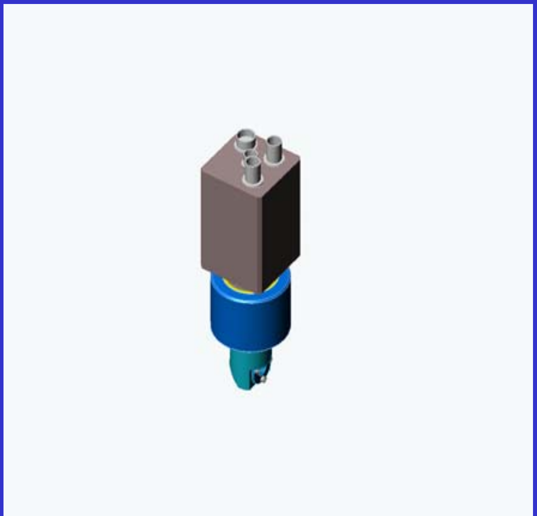
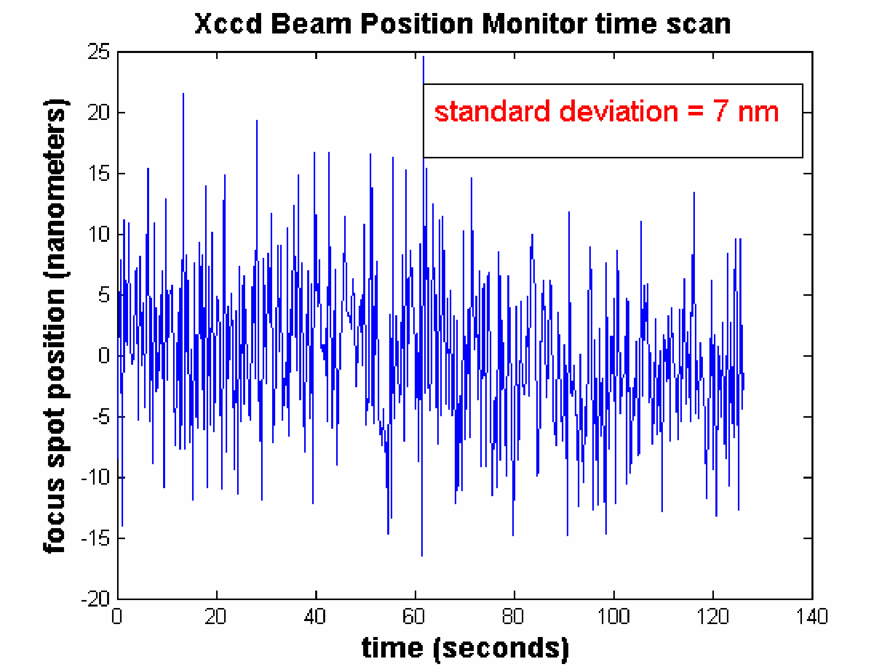
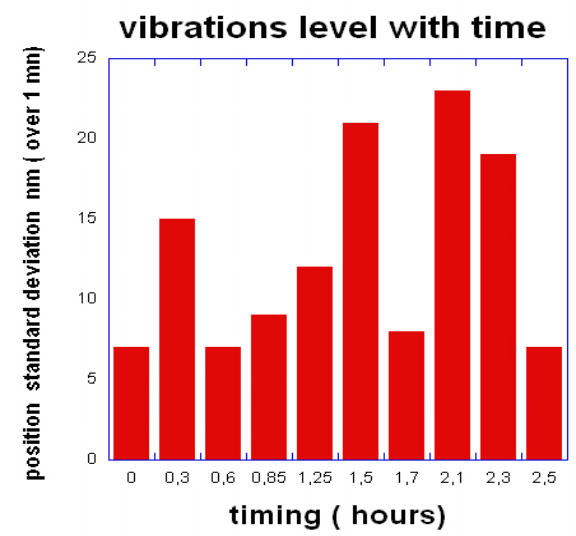


BPM XCCD camera  Integration time <1 ms

3nm rms position noise estimate





Vibrations environment was not adequate for this test

New design to be tested ≅ 20 nm

# Manufacturing – Metrology
# ESRF nanofocusing platform ( 6 KB systems - 40 nm)

ESRF

Start from (nearly) available technologies. incremental improvements

Closed loop figuring – metrology process

## Process steps

Substrate figuring – (bender attachment)
optical metrology
deterministic finishing
multilayer sputtering,
In situ Xray metrology
multilayer phase correction

# Fabrication processes used

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Smooth initial figuring
deterministic correction with
limited spatial resolution

Processes

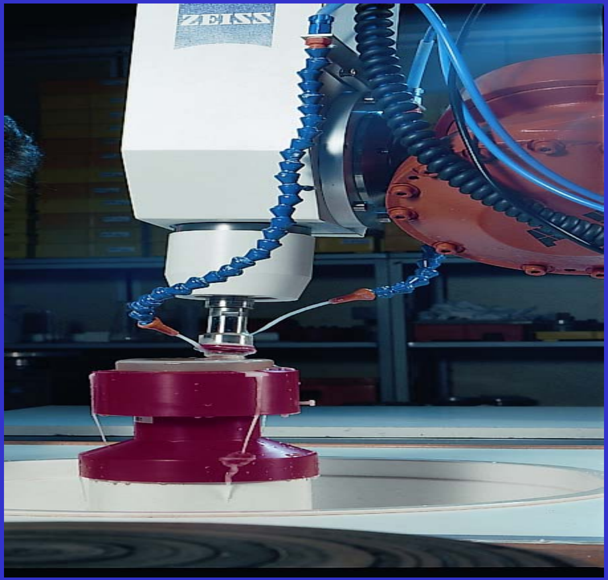
Computer control polishing
Differential Width profiling
Stressed polishing
Differential- profile coating
Ion beam figuring (IBF)

Partners

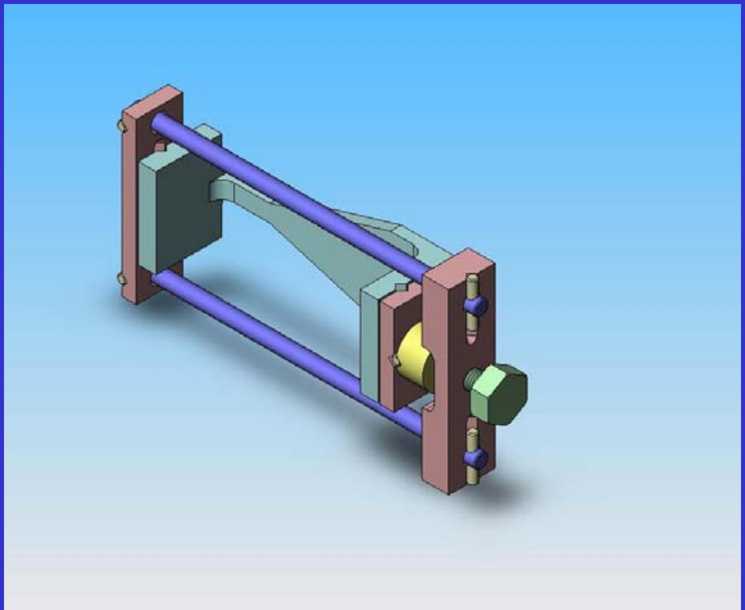
APS optics group
Zeiss
General optics
Crystal scientific
Winlight

# Figuring processes

Lapping / Polishing
Computer Controlled

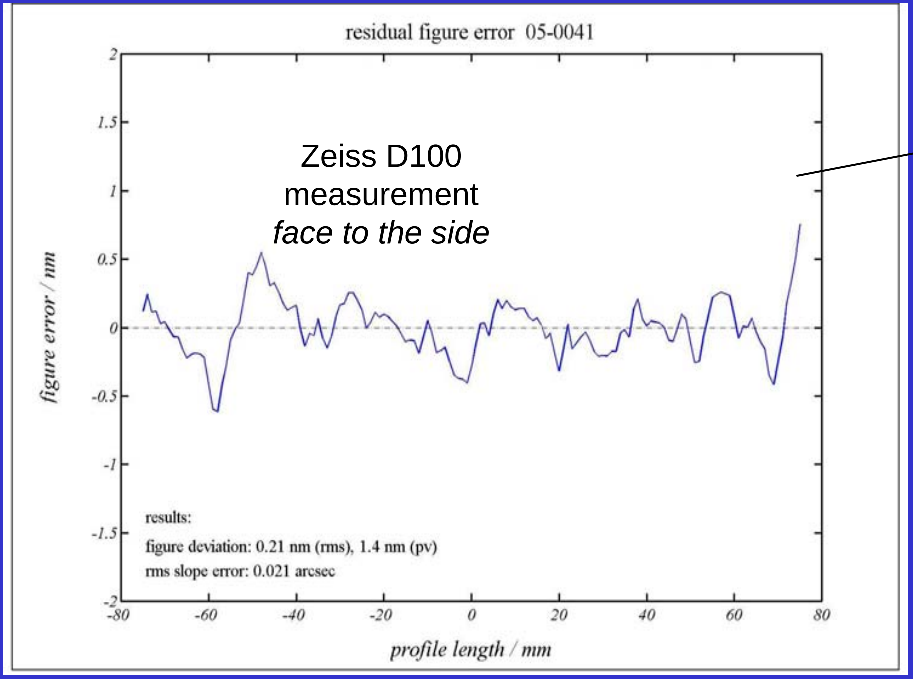


Stressed polishing



Ion Beam Figuring
Computer Controlled

# Zeiss IBF capability



Zeiss D100
measurement
*face to the side*

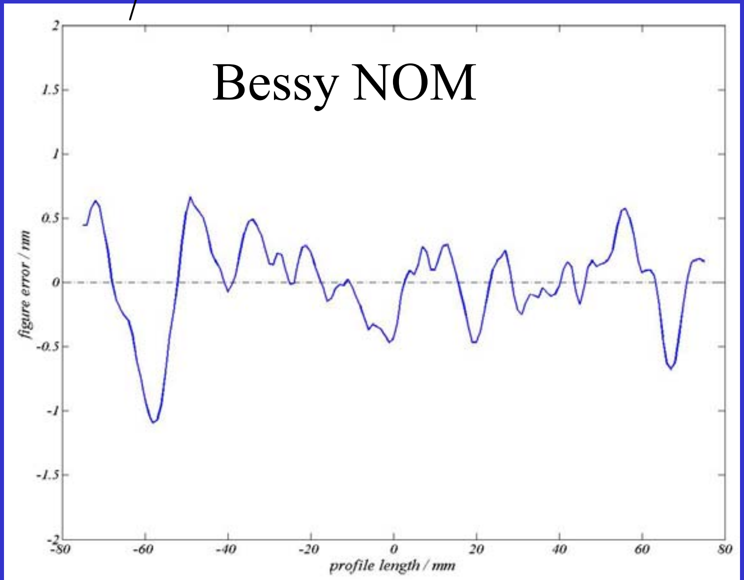
results:

figure deviation: 0.21 nm (rms), 1.4 nm (pv)

rms slope error: 0.021 arcsec

**Agreement in the sub-nm range !!!**

**Flat mirrors**

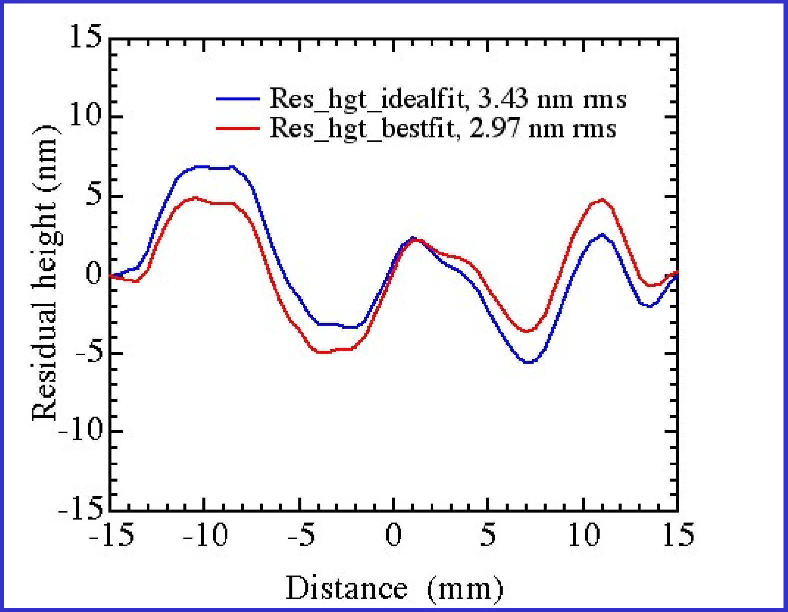


**Flat mirror for SPring8**

| **Results:** | **Zeiss D100** | **BESSY NOM** |
|---|---|---|
| Slope error | **0.10 µrad rms** | **0.13 µrad rms** |
| Residual figure error | **0.21 nm rms** | **0.56 nm rms** |
| | **1.4 nm pv** | **2.3 nm pv** |
| Radius | **60 km** | **61.2 km** |

# APS- ESRF profile coating KB project

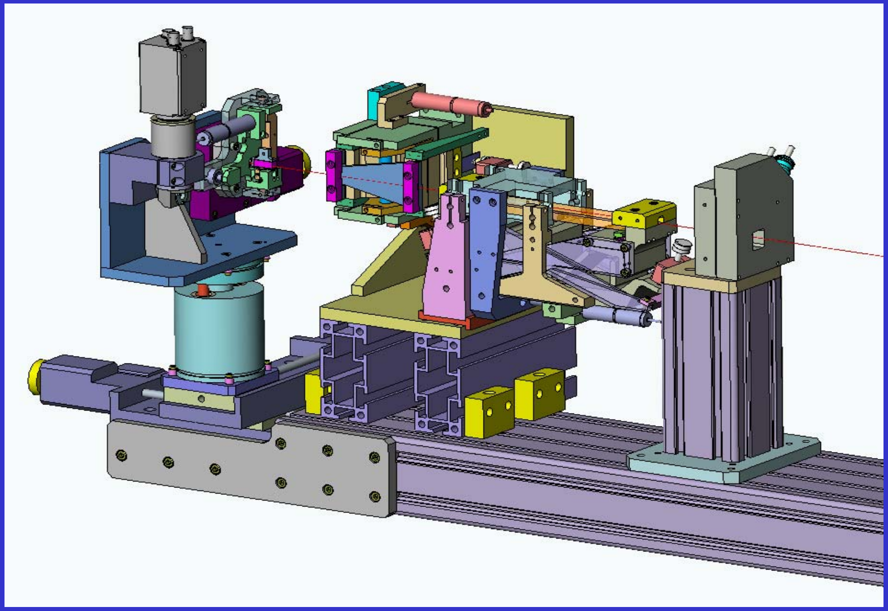
R.Conley



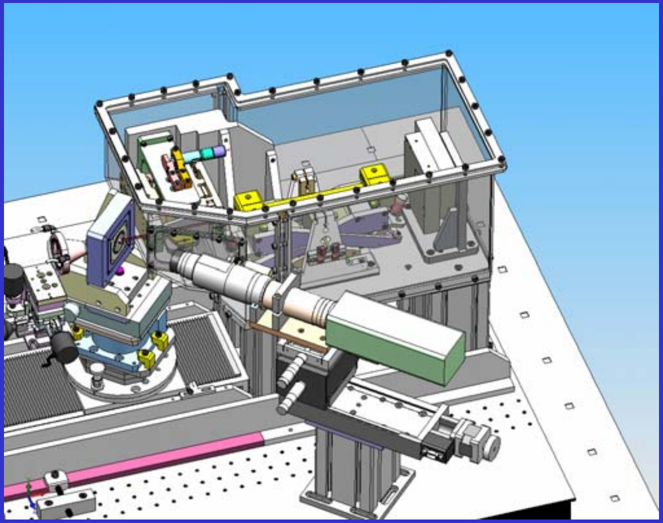
L.Assoufid

37 X 77 mm focal length mirrors

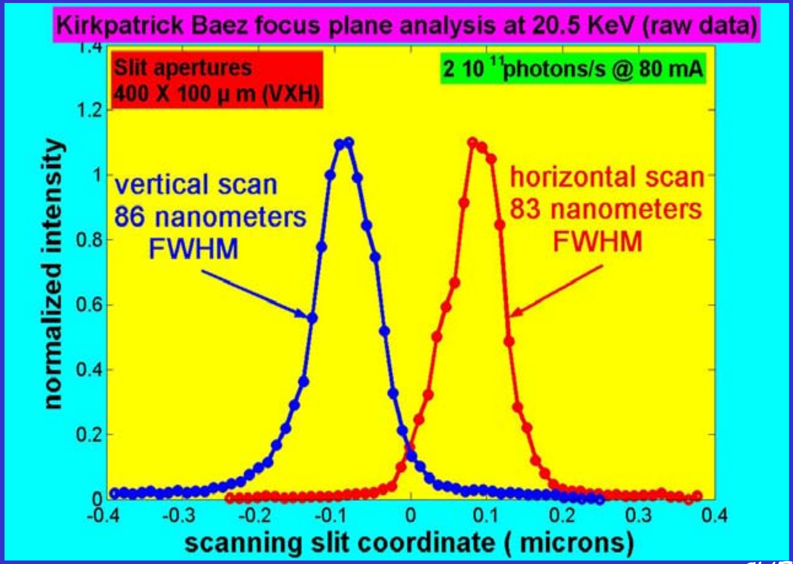
# Dynamic KB : starting from existing designs

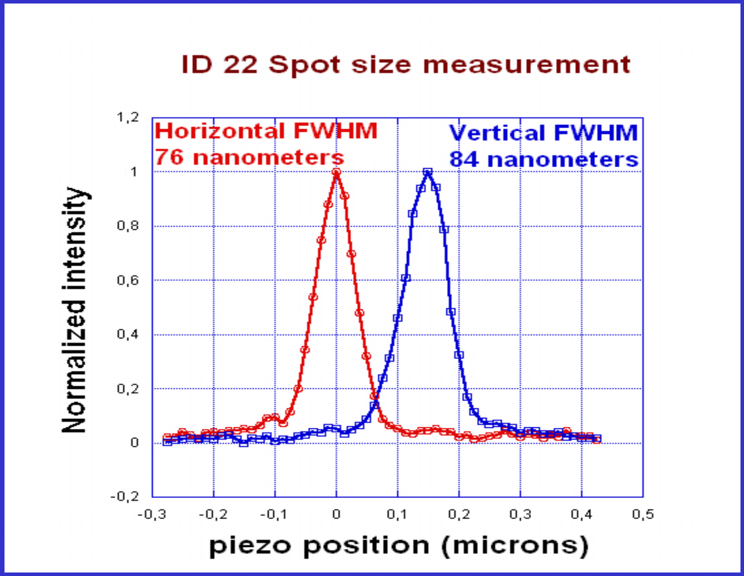


ID19 low beta source at 150 m
Energy 15 to 24 keV

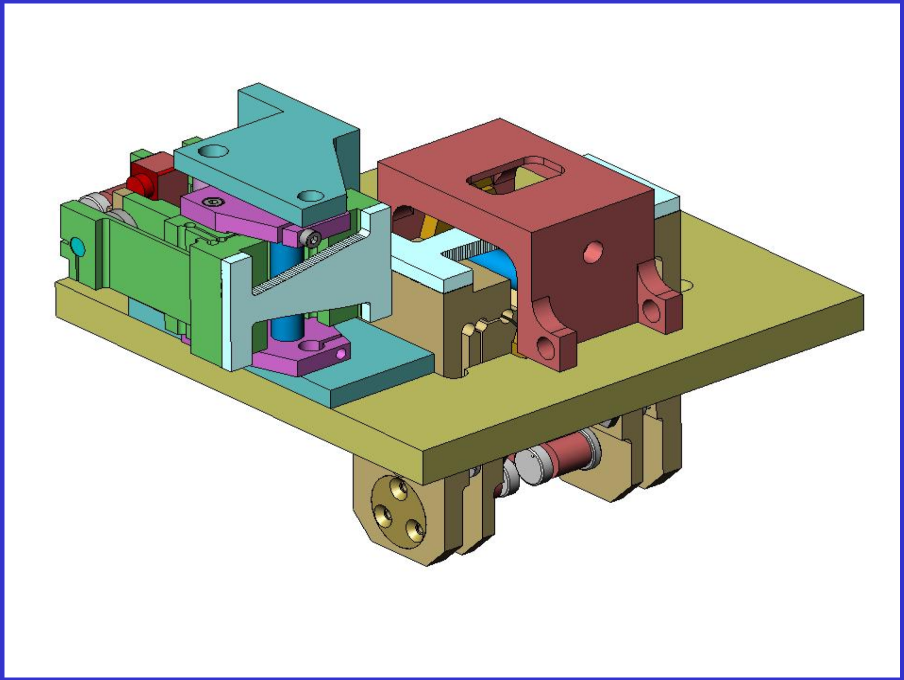


ID22 60 m high beta section
slitted source Energy 17 kev





# Shrinked design for dynamic KB



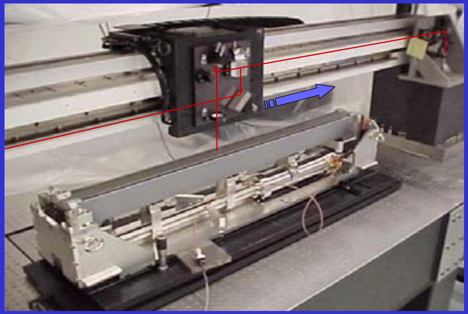
Improvements

Reduce focal length
Mirror figure errors
System vibrations
Temperature induced drifts - feedback

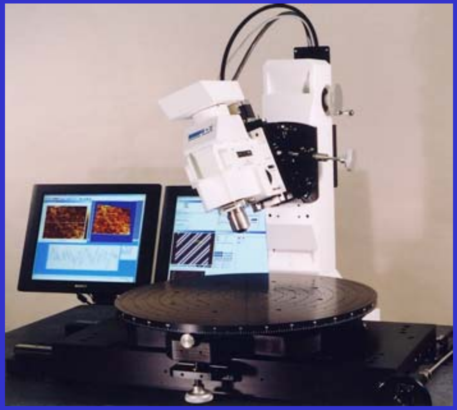
# Available metrology instrumentation for strong aspheres

Need : 0.1 nm rms accuracy

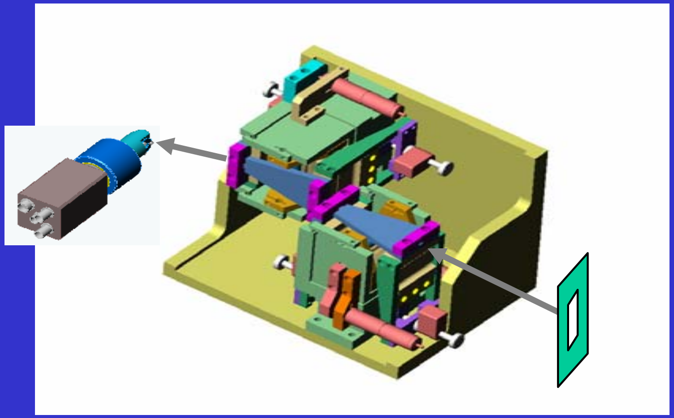
LTP accuracy being evaluated
(Round Robin)



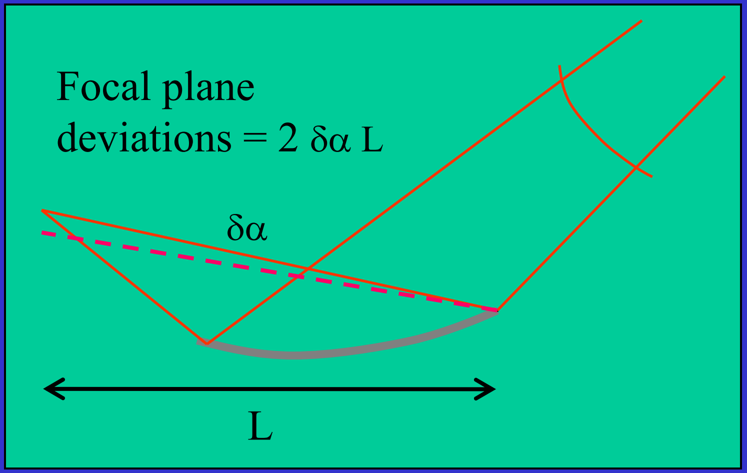
New commercial stitching interferometers
ADE phase shift , QED
Evaluated by L. Assoufid at APS



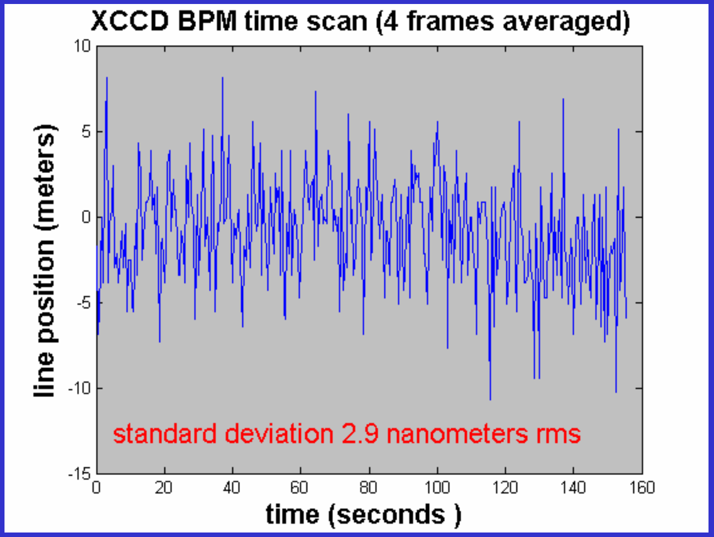
ESRF In situ Xray metrology
(many other wavefront methods
coming along)



# ESRF pencil beam In situ metrology (wavefront derivative )

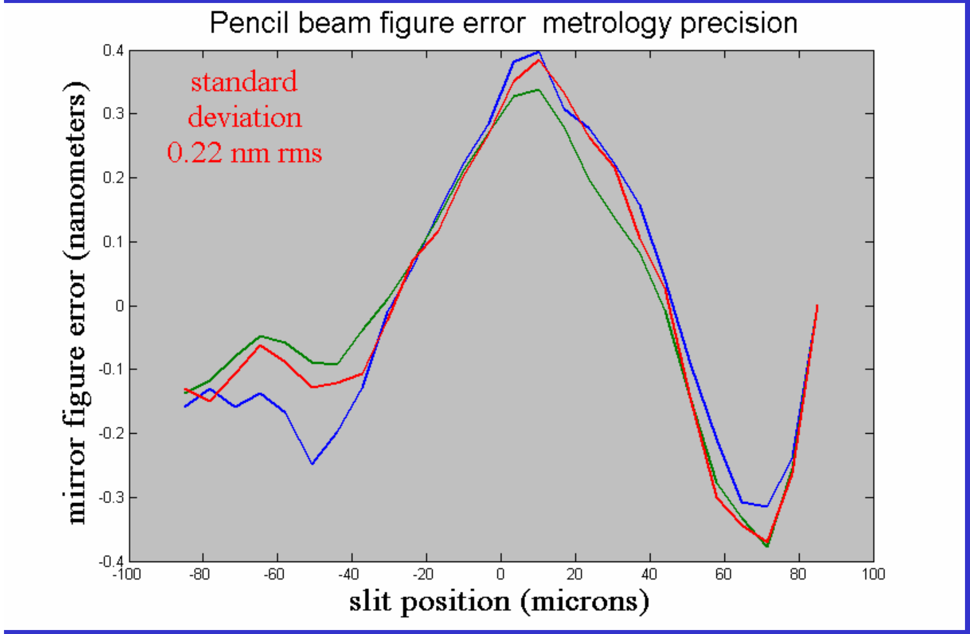


Focal plane
deviations = 2 δα L



XCCD BPM time scan (4 frames averaged)

standard deviation 2.9 nanometers rms



Pencil beam figure error metrology precision

standard
deviation
0.22 nm rms

80 mm FL multilayer (41 nm FWHM)

20 nanoradian rms slope precision

figure error repeatabilty over 36 mm :
0.15 nm PV (0.03 nm rms)

# Medium- long term perspectives

Static multilayers mirrors preferred

Substrate figuring : Zeiss, OSAKA U (JTEC) , TINSLEY
capability already at the nanometer level - Roughness to be confirmed

Multilayers : Very steep gradients and phase correction feasability to be proven

Metrology : Xray wavefront methods necessary and probably sufficient
much beamtime needed.

In situ figuring an attractive option

# Pooling of synchrotron sources resources ?

## Synchrotrons Challenge

Establish a predictable secure procurement for all process operations
keep control especially for metrology

Market is small with respect to needed investments

European FP7 initiative

Europe -US collaborations

Rely on what will be commercially available (OSAKA-JTEC)

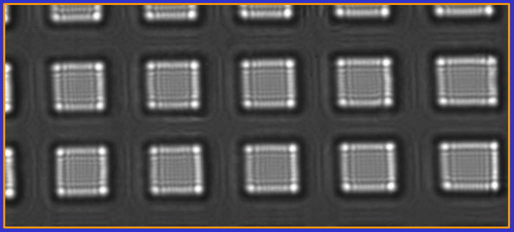
# *Application : projection microscopy*

## Fresnel diffraction pattern - Spot size limited resolution

*Energy = 19 keV*

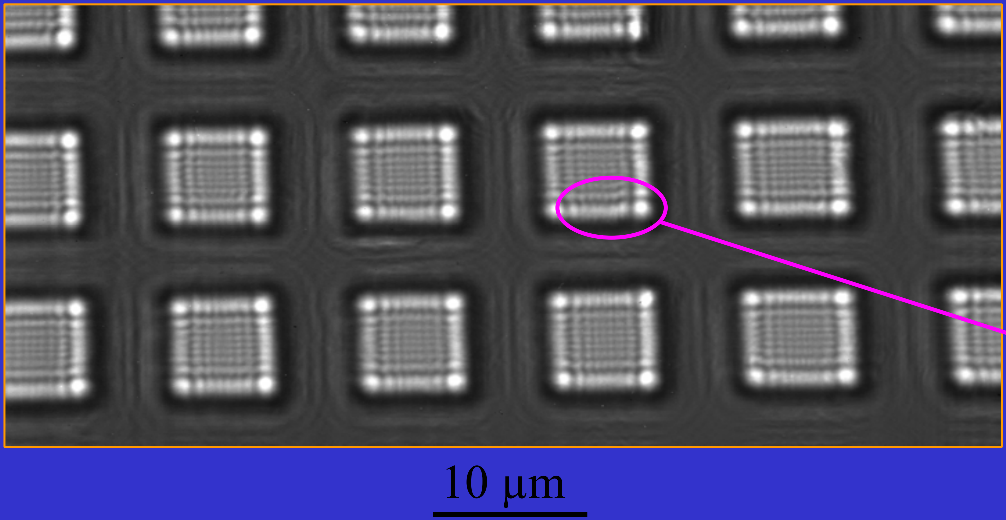
*Magnification*: $(z_1 + z_2)/z_1 = 3$

*Defocus*: $z_1 z_1/(z_1 + z_2) = 22$ mm



*M* = 9

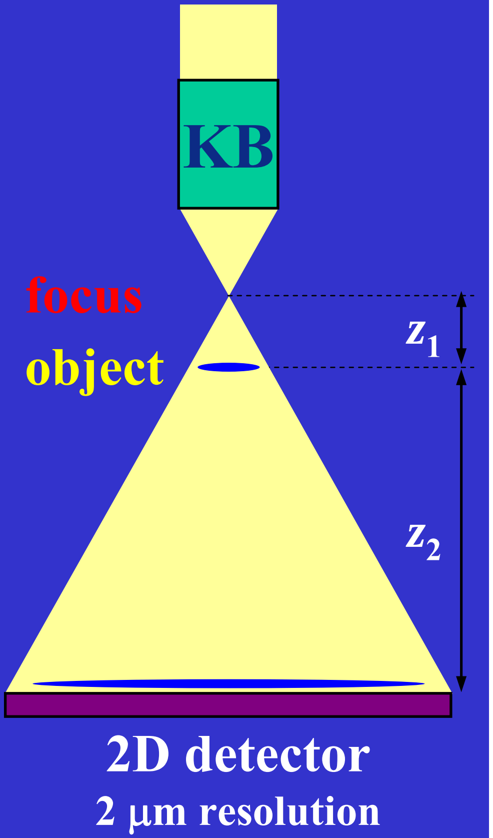
*D* = 29 mm



*M* = 18

*D* = 31 mm

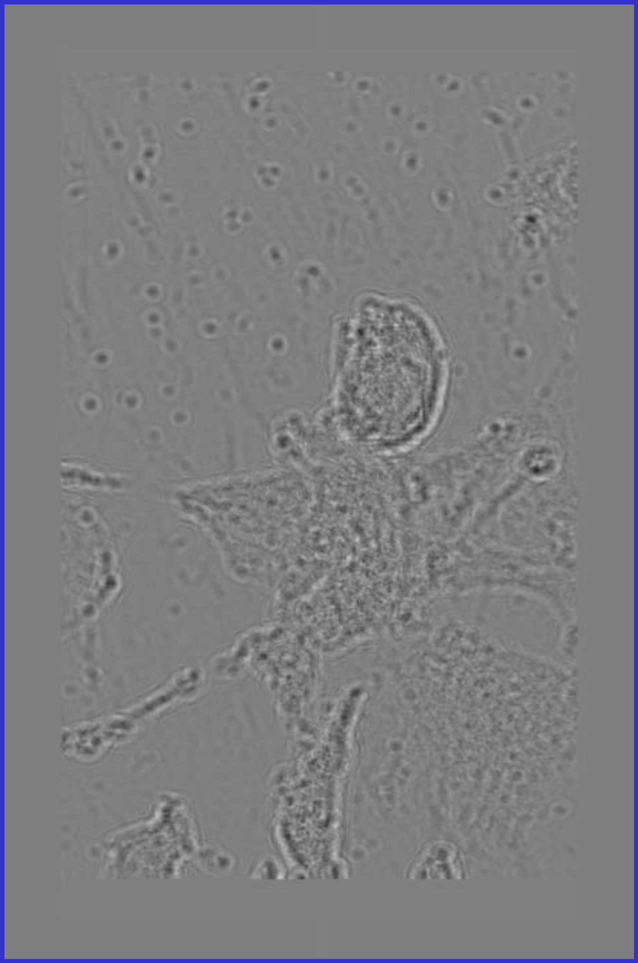
**Defect of grating on a 100 nm scale revealed**



P. Cloetens, O. Hignette

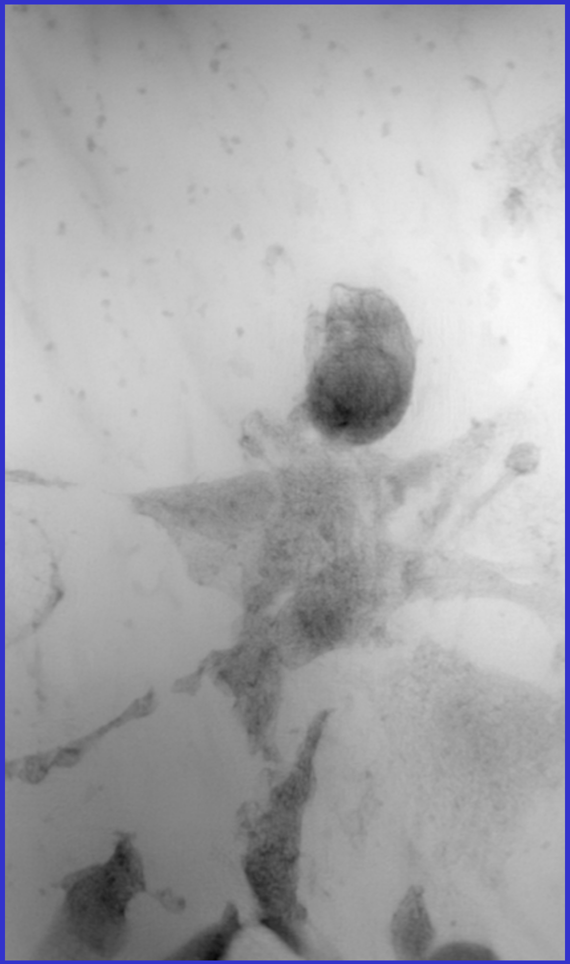
# Phase Retrieval

## Possible single shot imaging with a priori information



$D = 45$ mm

5 distances



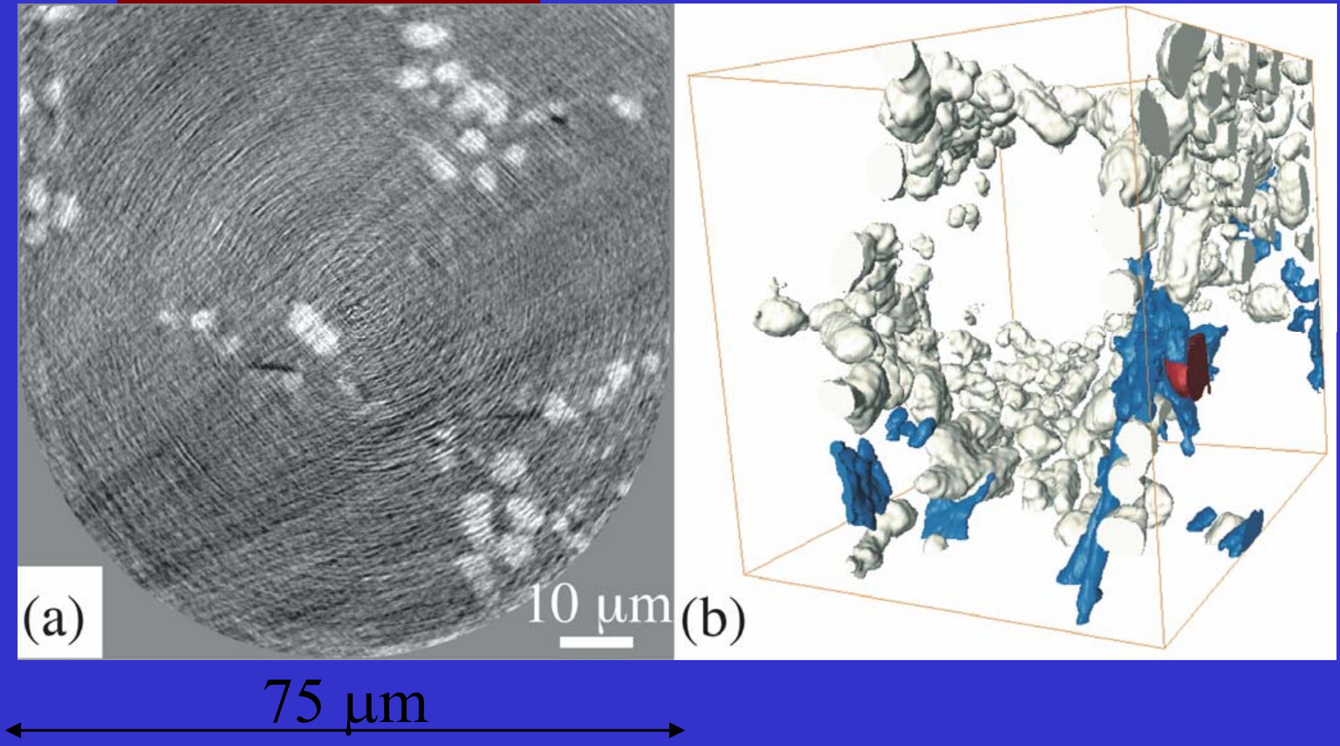
Rel. Phase Map

**Neuron cell**

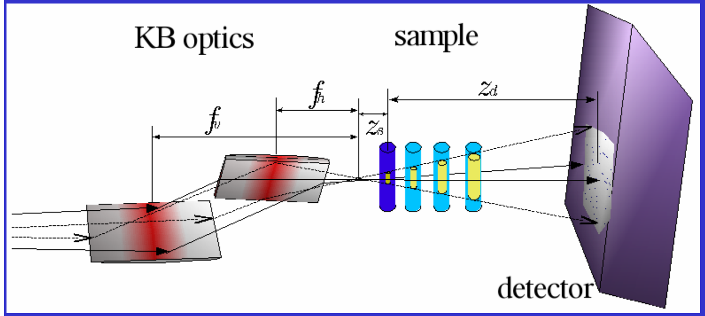
# Application example : Magnified Tomography on ID19 (projection imaging)

## Al / Si alloy

tomographic slice



**Si**
**Pore**
**$Al_5FeSi$**



Inside ϕ = 1 mm sample → local tomography!

$E$ = 20.5 keV

X-ray magnification ~ 80 (voxel size = 90 nm)

R Mokso et al, submitted to Appl. Phys. Lett

# Conclusions

Reflective optics technology is now a serious candidate
for < 10 nm nanofocusing

Most needed technologies have been proven at a research level

1 nm goal needs huge (coordinated) efforts but not a total dream

How and where to put resources to establish

Full processes control

## Acknowledgements

C.Morawe, P.Cloetens, R.Baker, A.Seifert, L Assoufid, R.Conley

ESRF

# Technologies developped at ESRF
# Short term KB nanofocusing projects

| system type | coating | focal length HXV(mm) | energy range kev | spot size (nanometers) |
|---|---|---|---|---|
| dynamic | multilayer | 83 X 180 | 13 - 25 | 50 X 50 |
| dynamic | multilayer | 160 X 360 | 10 - 14 | 300 X 200 |
| dynamic | multilayer | 240 X 100 | 50 - 100 | 300 X 40 |
| dynamic | Pt | 80 X 177 | 10 - 14 | 200 X 200 |
| static | Ni | 60 X 150 | 2.5 - 7.5 | 200 X 100 |
| static | Pt | 37 X 77 | 10 – 14 | 50 X 50 |