Optical and "At Wavelength" metrology R&D @ NSLSII

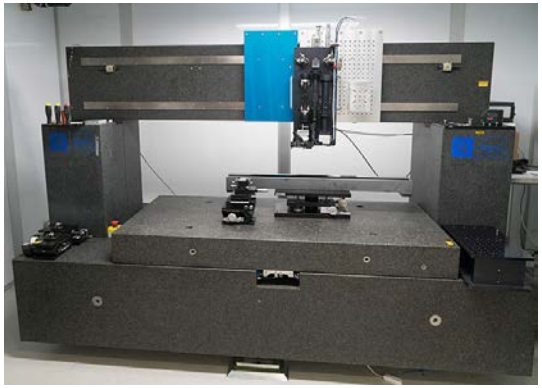
Mourad IDIR, NSLS-II

Beamline Engineering Meeting,
BNL, March 25-26, 2019

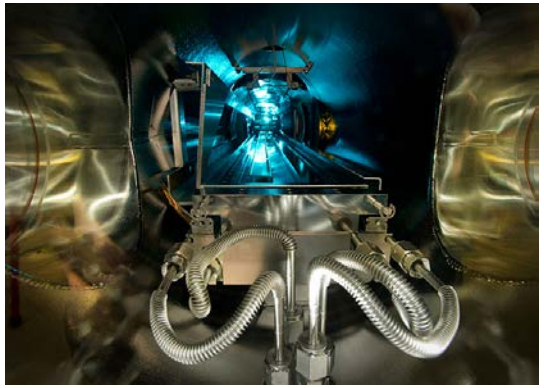
U.S. DEPARTMENT OF ENERGY | Office of Science
BROOKHAVEN NATIONAL LABORATORY

Experimental Development Groups

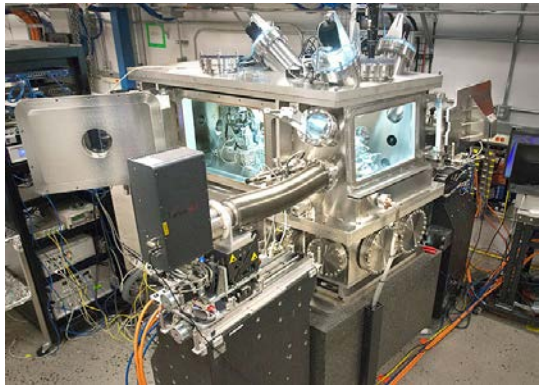
https://www.bnl.gov/ps/groups/rd/



Optical and At Wavelength Metrology



Optics Fabrication



Precision Engineering and Nanopositioning

- Source & X-Ray Optics Simulations (Oleg Chubar)
- Refractive lenses (Ken Evans-Lutterodt)
- Detectors (Peter Siddons)
- Engineering (Steve Hulbert)

NSLS-II Optics and Metrology Group

EXPERIMENT DEVELOPMENT
W.-K. Lee
PROGRAM MANAGER

D. Carlson
O. Chubar
J. Keister
W. Struble

BEAMLINE ENGINEERING
S. Hulbert (I)
GROUP LEADER
S. Antonelli
D. Bacescu
S. Coburn
C. Eng
E. Haas
L. Lienhard
M. Lucas
S. O'Hara
Y. Zhu

RESEARCH OPERATIONS SUPPORT
M. Buckley
GROUP LEADER
C. Ali (JS)
M. Bromfield
S. LaMarra
S. Sherwood
R. Smith

DETECTORS
D.P. Siddons
GROUP LEADER
A. Kuczewski
R. Michta
A. Rumaiz

OPTICS & METROLOGY
M. Idir
GROUP LEADER
L. Huang
S. Qian
K. Tayabaly
T. Wang

N. Bouet
M. Vescovi
J. Zhou

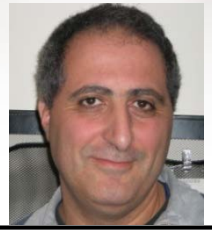
E. Nazaretski
D. Kuhne
Wei Xu
Weihe Xu

Experimental Development Goup

- Metrology
- Optics fabrication
- Precision Engineering and nanopositioning

https://www.bnl.gov/ps/groups/rd/

Optics R&D and Metrology Group



Group Leader
Physicist
M. Idir

Optics Metrology Group mission:
develops, tests, and operates tools to measure, and correct, the relevant properties of optical elements used in synchrotron radiation beamlines

Lei Huang
Associate scientist
Optical Metrology

Kashmira Tayabaly
Post Doc
Jan. 19 –Jan 21

Tiany Wang
Post Doc
Optical Metrology

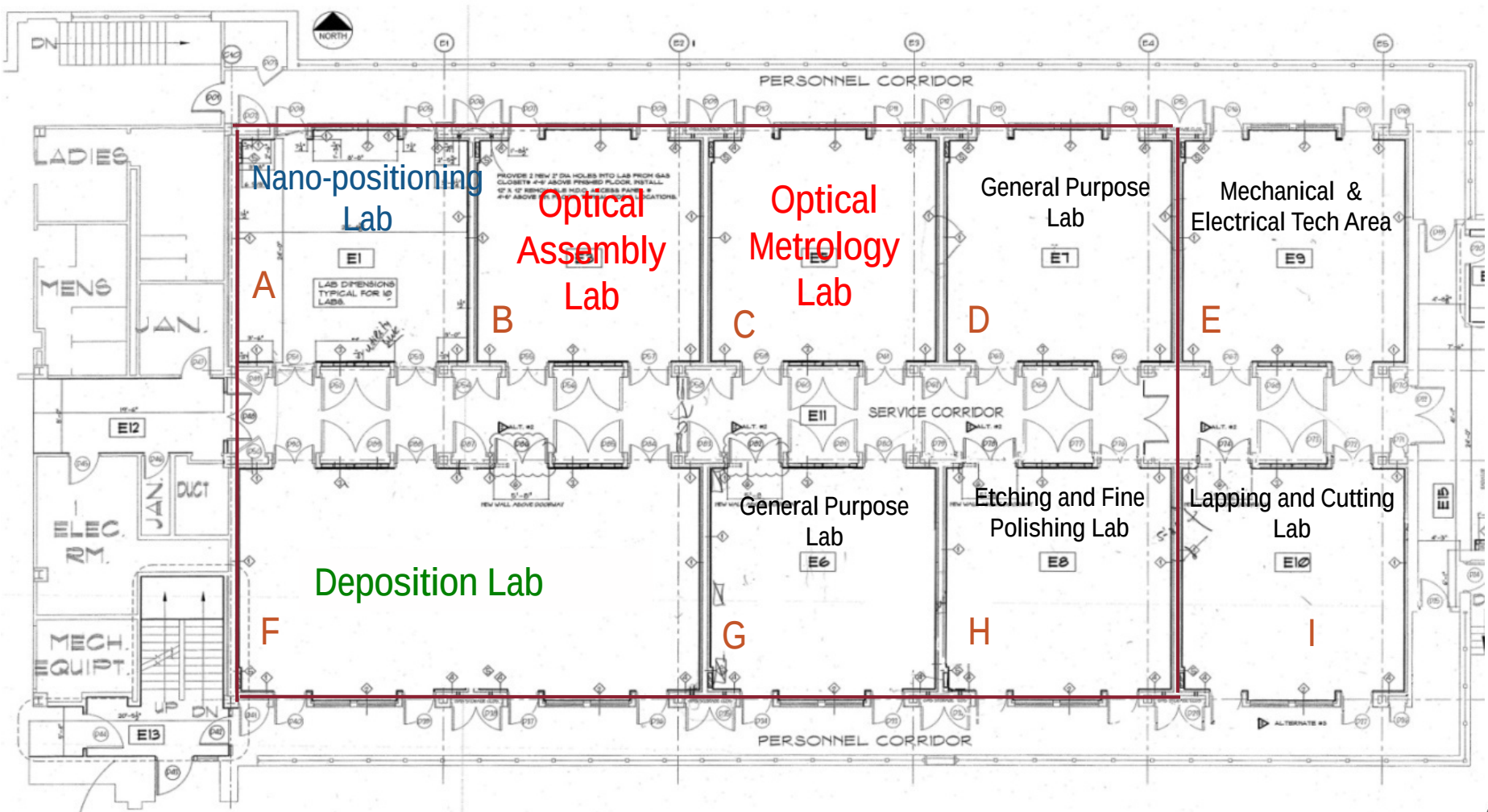
April 18 – April 20

NSLS-II Experimental Facilities R&D Program

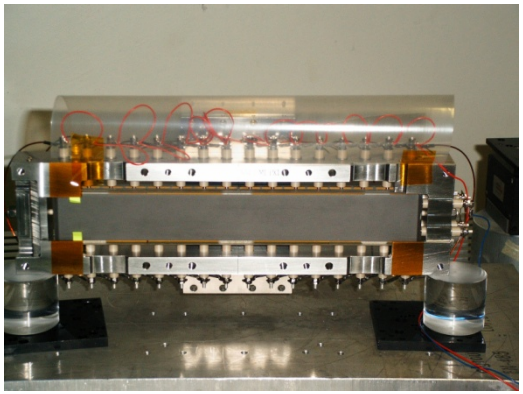
R&D Labs: Total ~5000 ft2 space, incl. 4,200 ft2 ISO 7 (Class 10000) clean rooms

900 ft2 space for the Optical Metrology Lab (~ 85 m2)

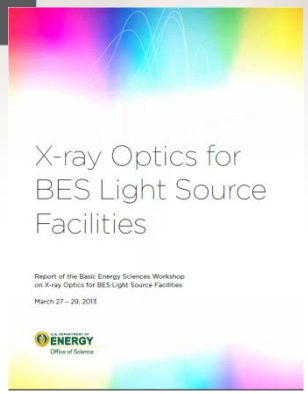
900 ft2 space for the Deposition Lab.



Optical and "At Wavelength" metrology R&D



Why we need to develop Metrology?



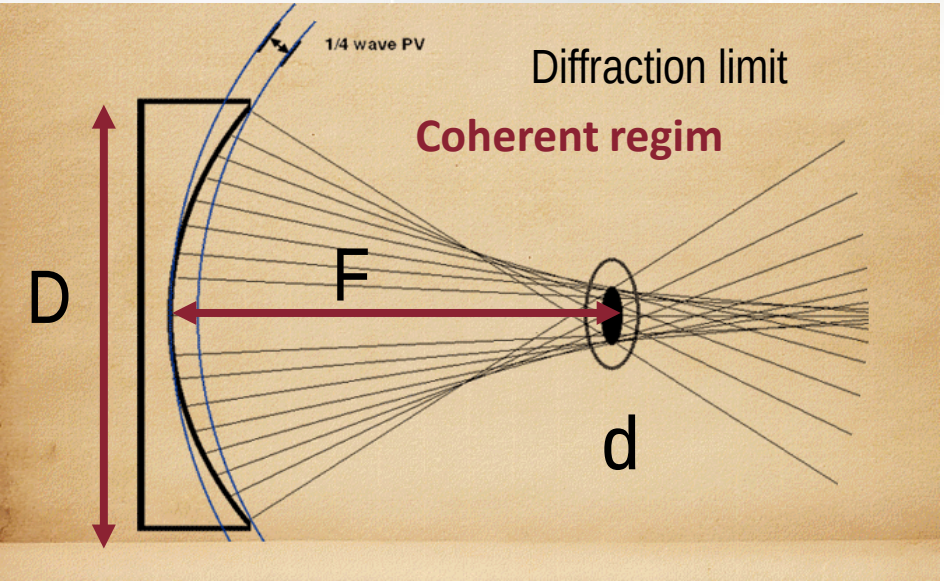
March 2013

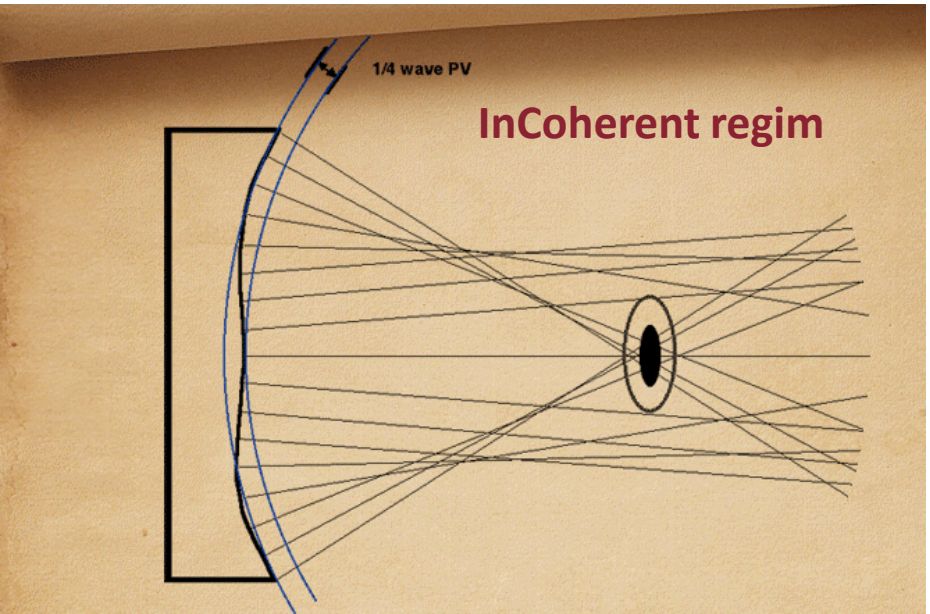
Maintaining the brightness of synchrotron and free electron laser (FEL) X-ray sources requires optical elements manufactured to very high tolerance that maintain their characteristics under beamline operational conditions. To do this, we need methods to measure the characteristics of optical elements, such as figure error and mirror roughness, or the phase coherence of diffractive optics, such as gratings.

- **Development of next generation of metrology tools and techniques:** This is essential to enable measurements of figure errors at sub 100-nrad levels. This will be done by combining upgraded instrumentation in the existing NSLS-II optical metrology laboratory with a new at-wavelength measurements capability to be established at the Metrology and Instrumentation Development (MID) beamline at NSLS-II. The at-wavelength wavefront characterization techniques will open up perspectives, for instance, in the in situ optimization of adaptive optics or correction of reflective optics and could also be used as an online setup permitting focusing optimization, for example, by assisting in the alignment of critical x-ray optical components or compensating for the astigmatism of an incoming beam or mechanical deformation due to heat load or mounting stress.

Rayleigh Criteria Mirror Shape error <λ/8θ PV → ~ 4nm <λ/8θ PV

Marechal Criteria Mirror Shape error <λ/28θ rms → ~ 1.1 nm <λ/28θ rms





λ = 0.1 nm θ = 3 mrad L = 100 mm F = 100 mm

$$d \approx 0.6\lambda \frac{F}{D}$$

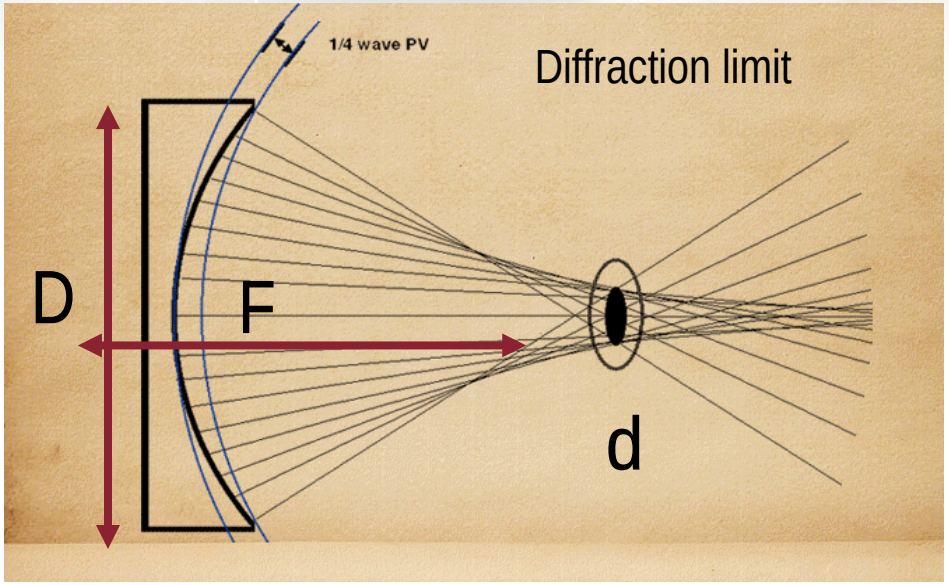
$$d \approx 20\ nm$$

2.Slope.F < 20 nm

Slope < 100 nrad rms

Height < 1.1 nm rms

Coherent regim



$$d \approx 0.6\lambda \frac{F}{D}$$

$$d \approx 20\ nm$$

Mirror Shape error $\lambda/28\theta$ rms

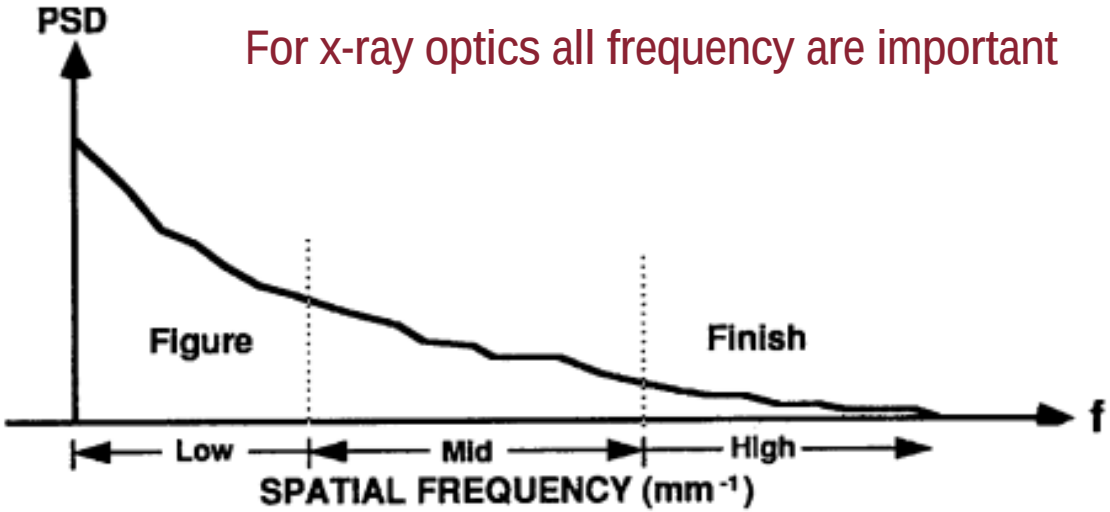
Soft x-ray: $\lambda = 1$ nm $\theta = 30$ mrad

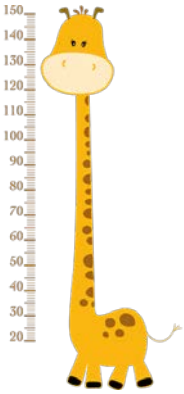
Hard x-ray: $\lambda = 0.1$ nm $\theta = 3$ mrad

NSLSII Metrology tools

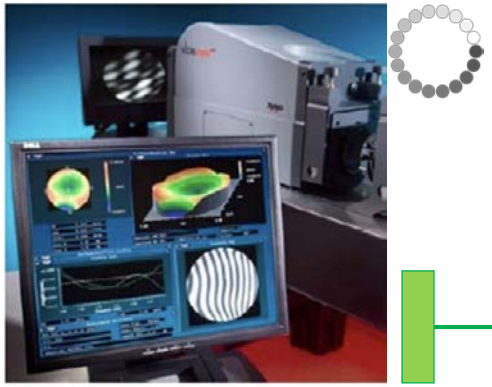
Effect of the surface quality differs on each spatial frequency regime

For x-ray optics all frequency are important





Height



Fizeau Interferometer

100 mm

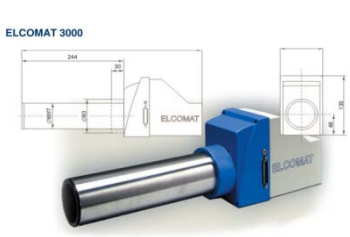
White Light Interferometer

2 mm

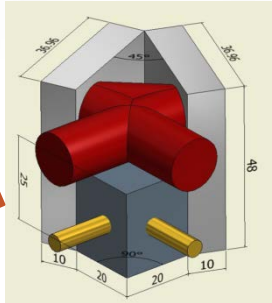
AFM

Slope measuring profilers

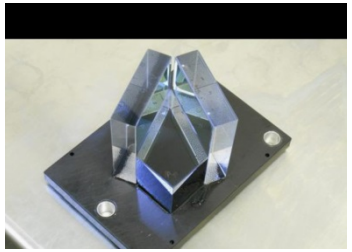
NOM



High accuracy Autocollimator

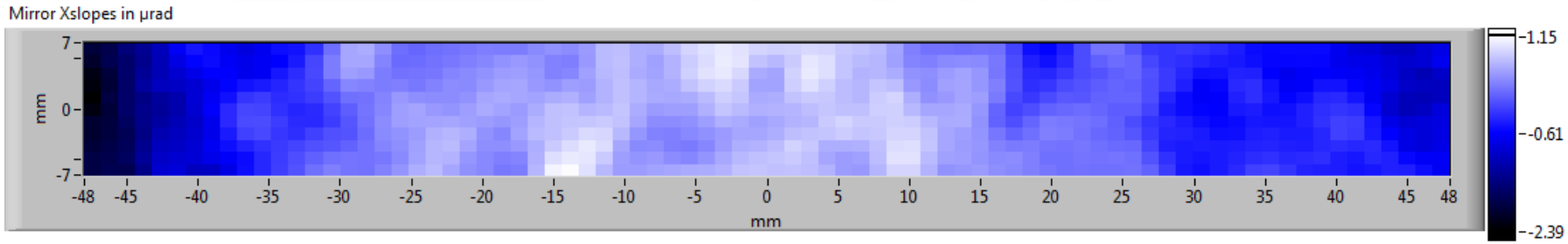


Stitching Shack Hartmann Optical Head : SSHOH

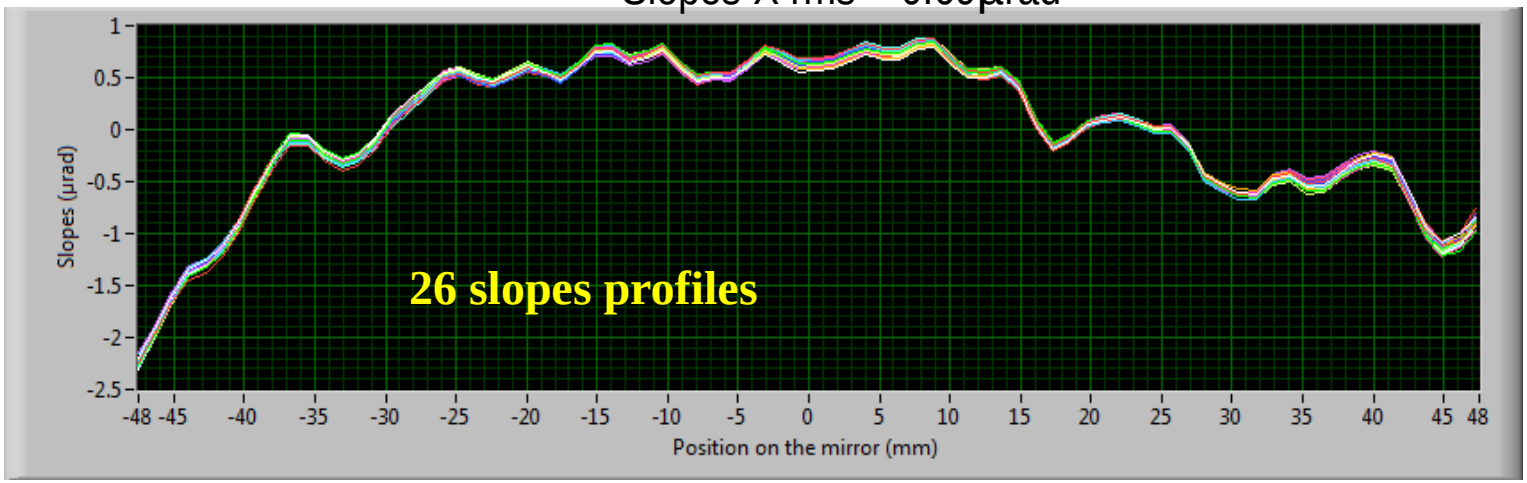


Results on a flat mirror:Repeatability

Average of 26 scans on a flat mirror (100mm long)



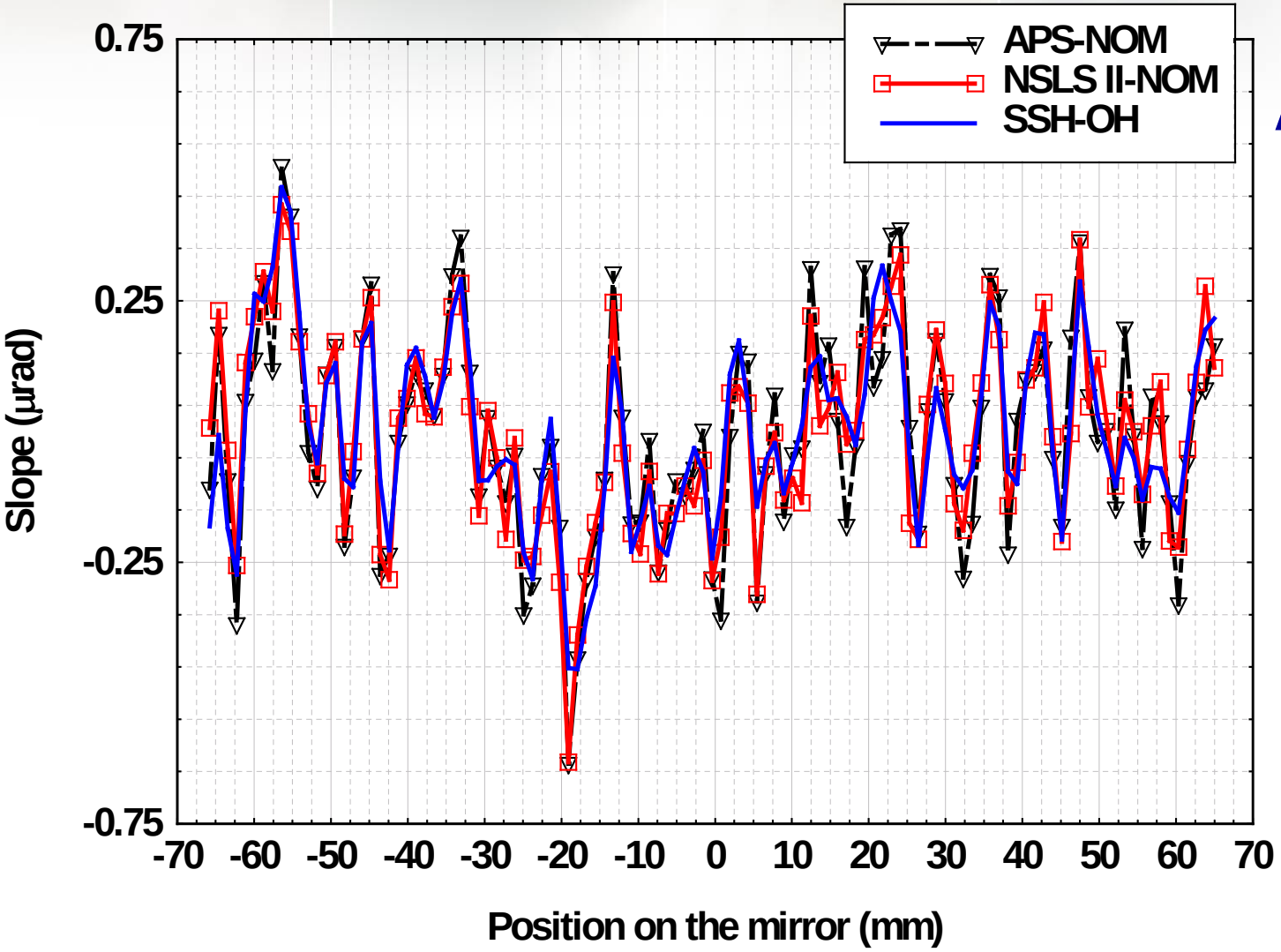
Slopes X rms = 0.69µrad



26 slopes profiles

30 nrad rms of repeatability obtained after subtracting best sphere

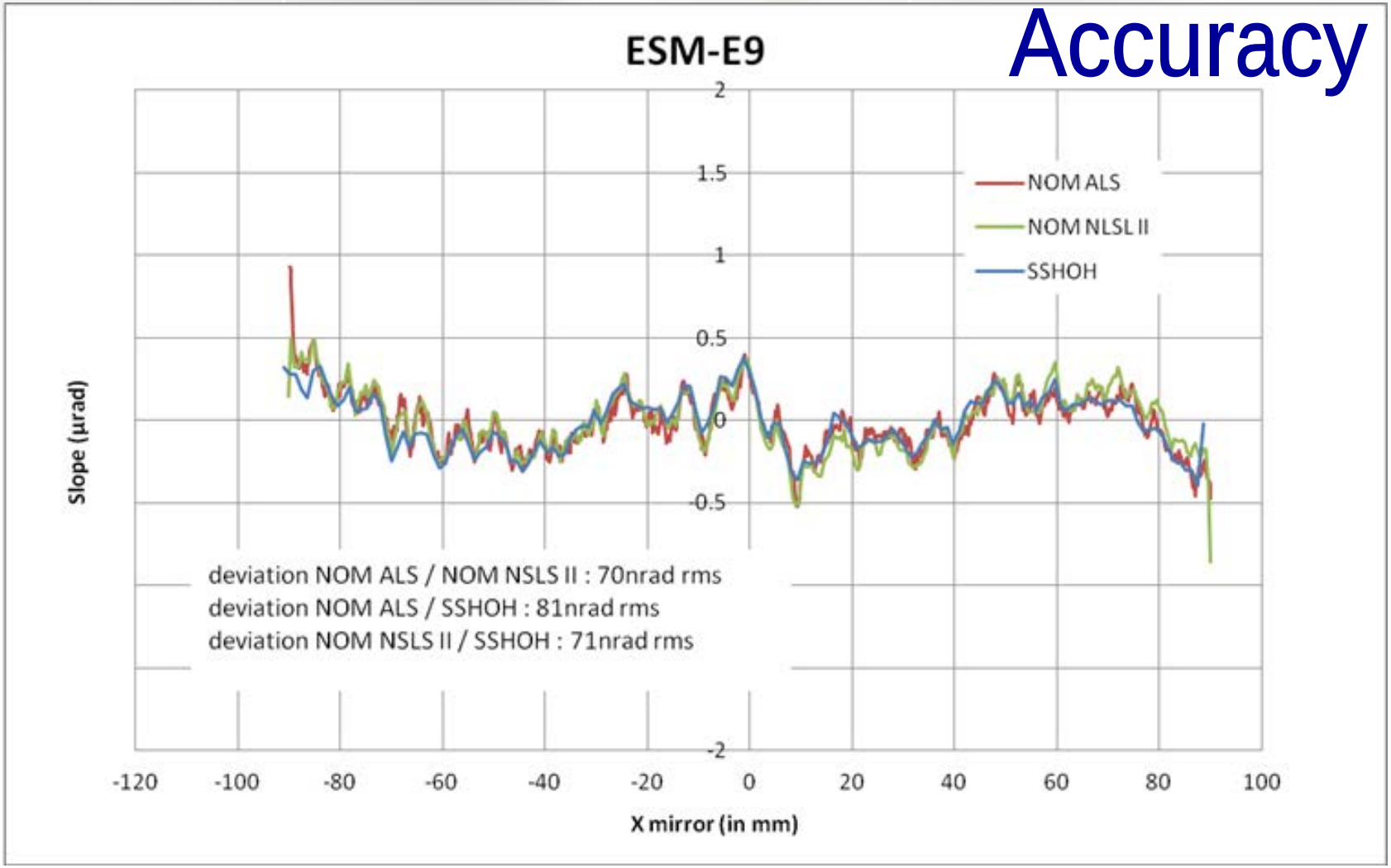
NSLS II NOM – APS NOM – NSLSII SSHOH



Accuracy

Difference between instruments : 80 nrad rms

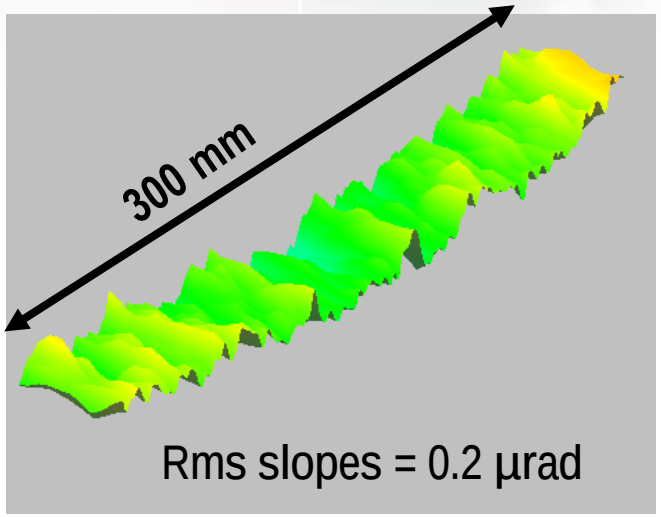
NSLS II NOM – ALS NOM – NSLSII SSHOH



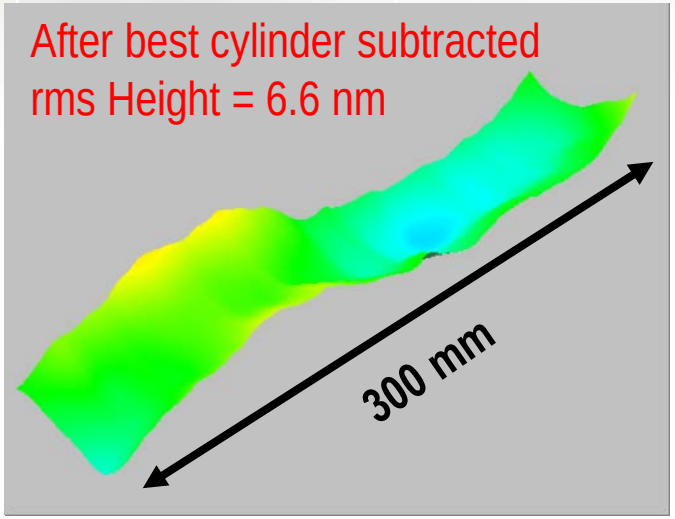
NSLSII SSHOH
with Stitching interferometry

Accuracy

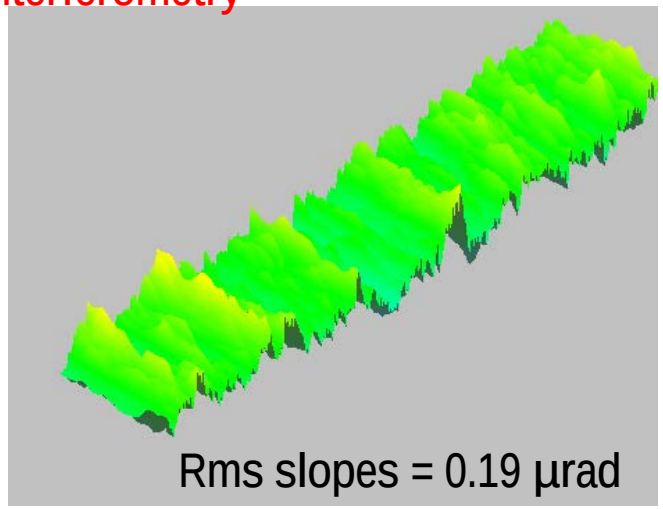
SSH-OH

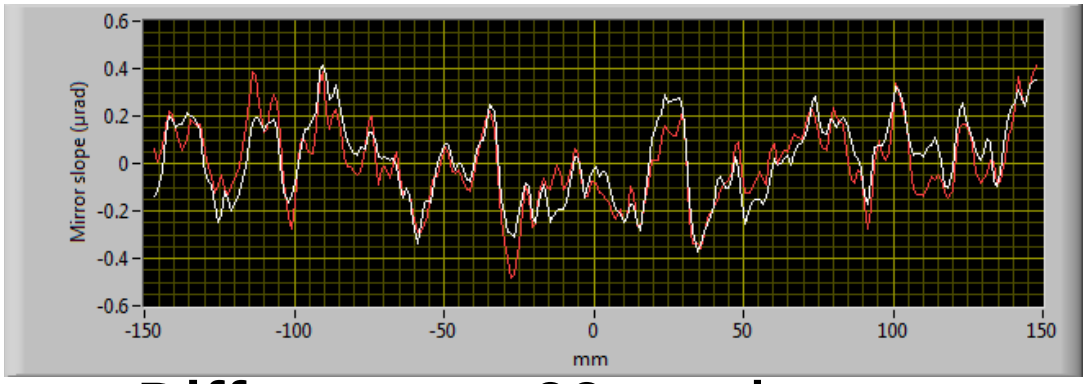


Measurement time < 40'



Interferometry

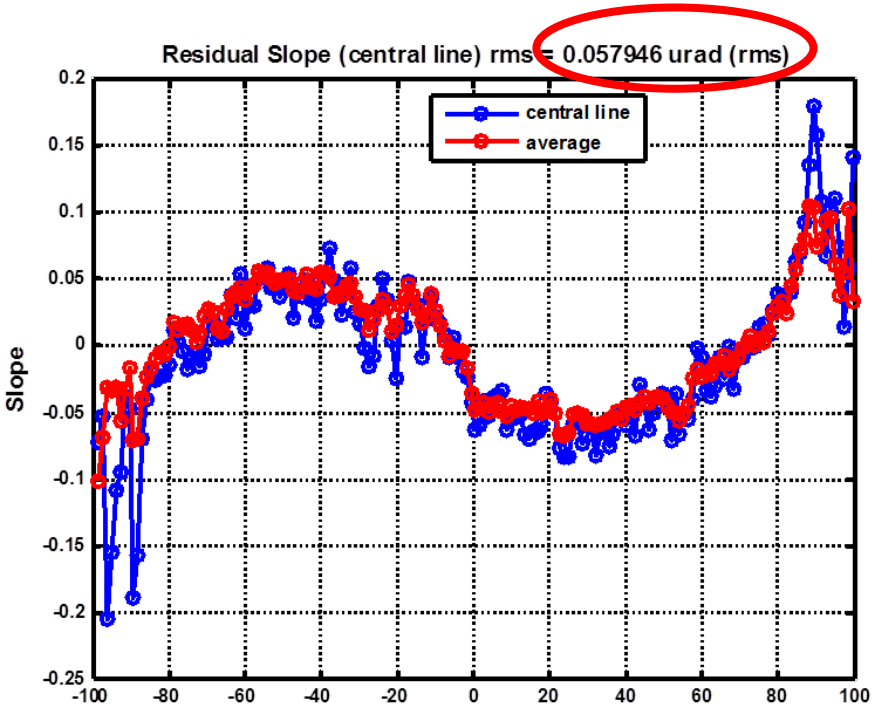


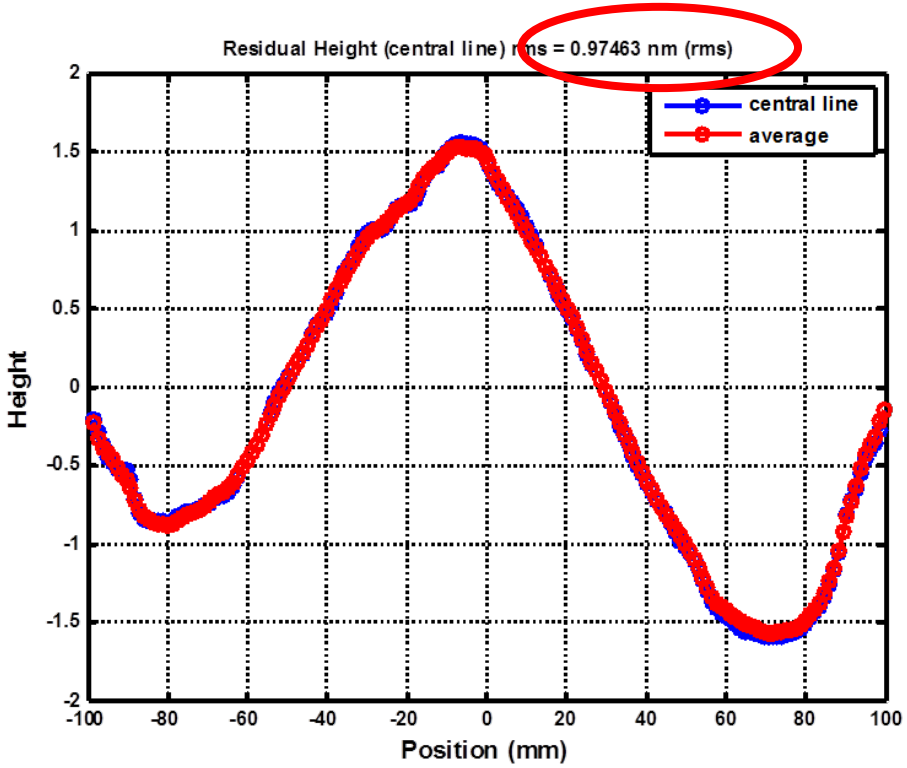


Difference = 83 nrad rms

Grating Blank substrate

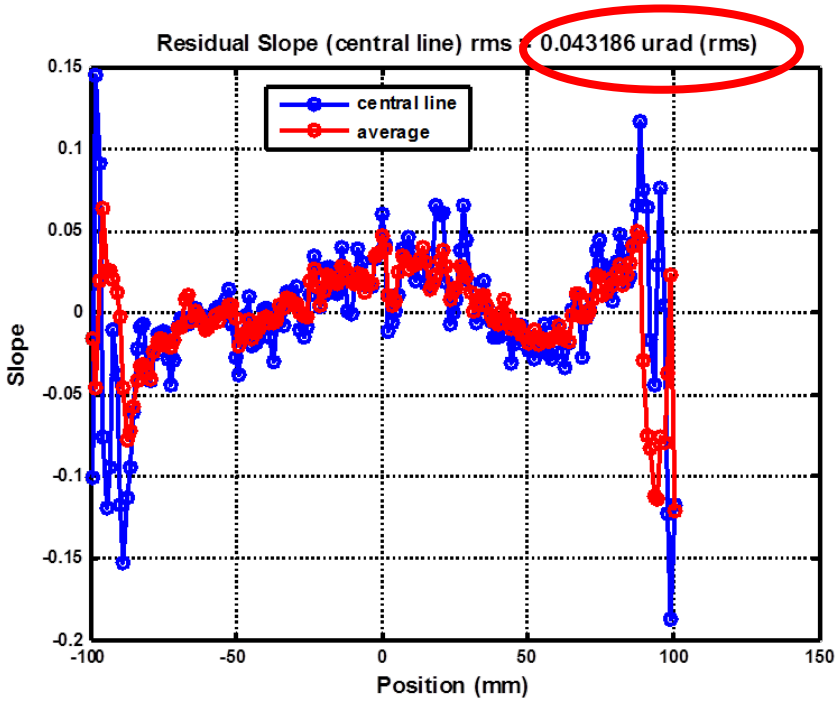
VFM Geometry

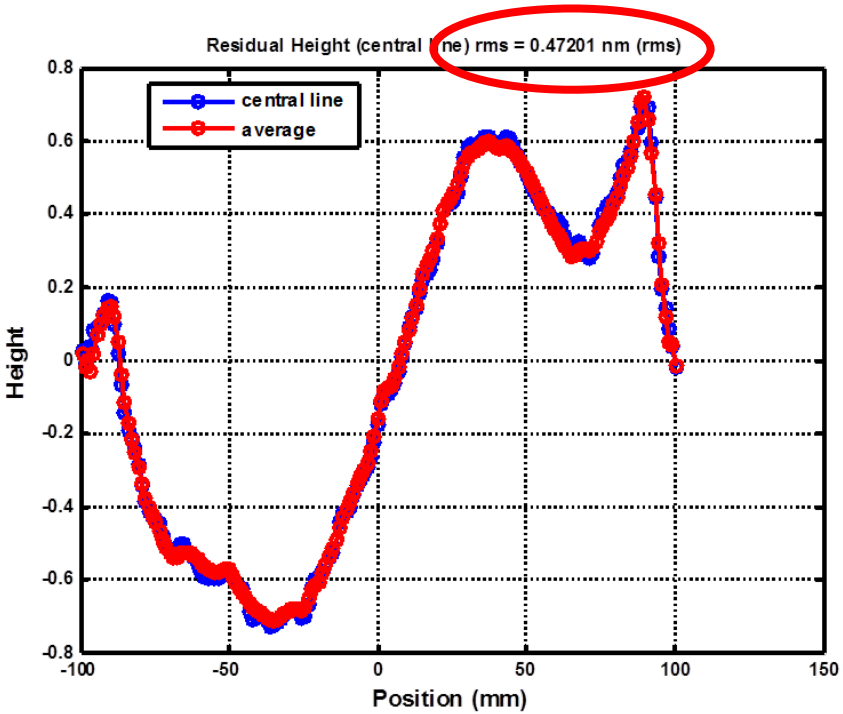




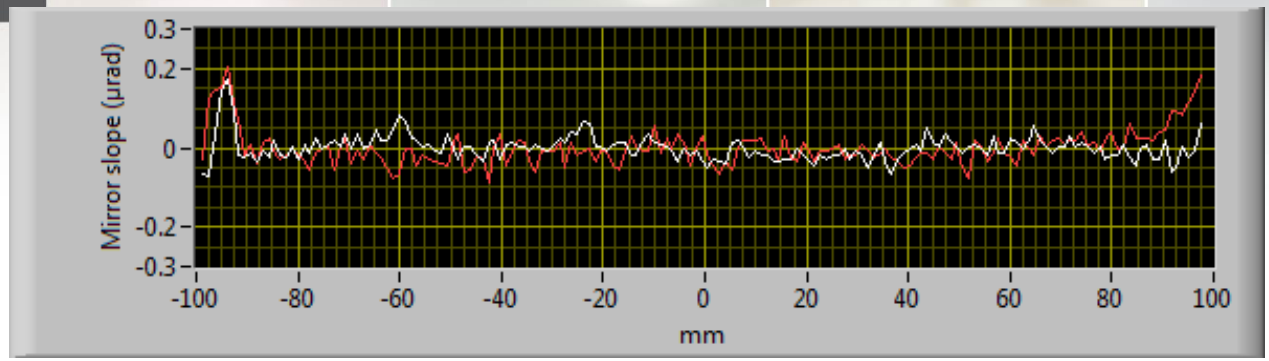
Grating Blank substrate

HFM Geometry

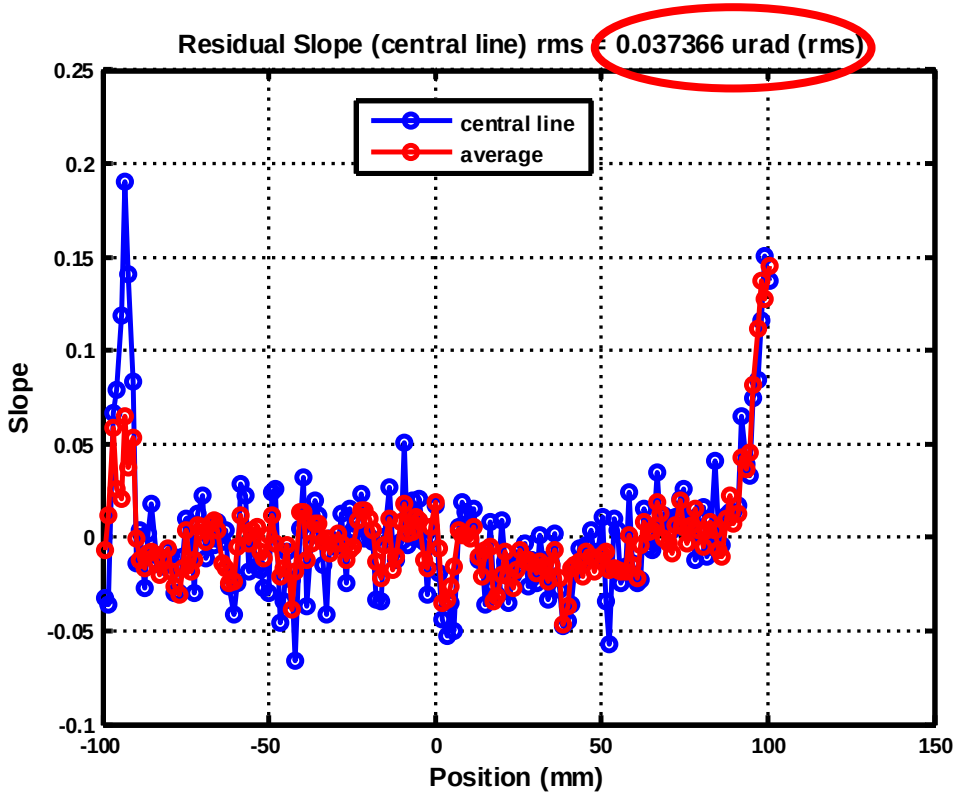


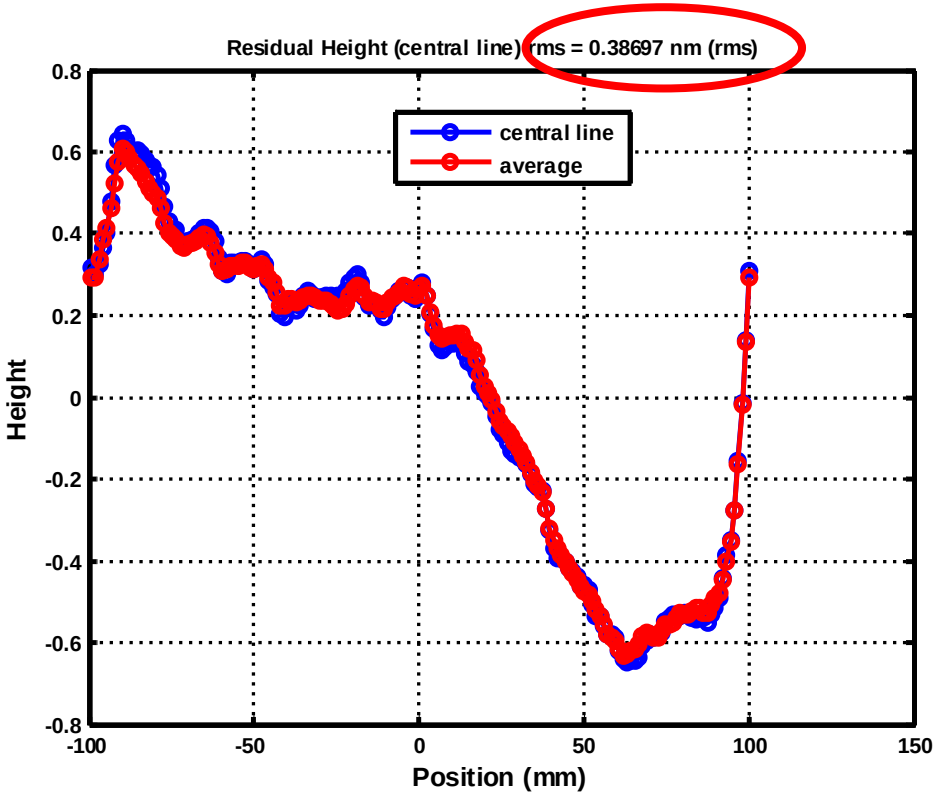


Grating Blank substrate



SIX1 over 200mm
Difference between AB et BA
is *25 nrad rms*

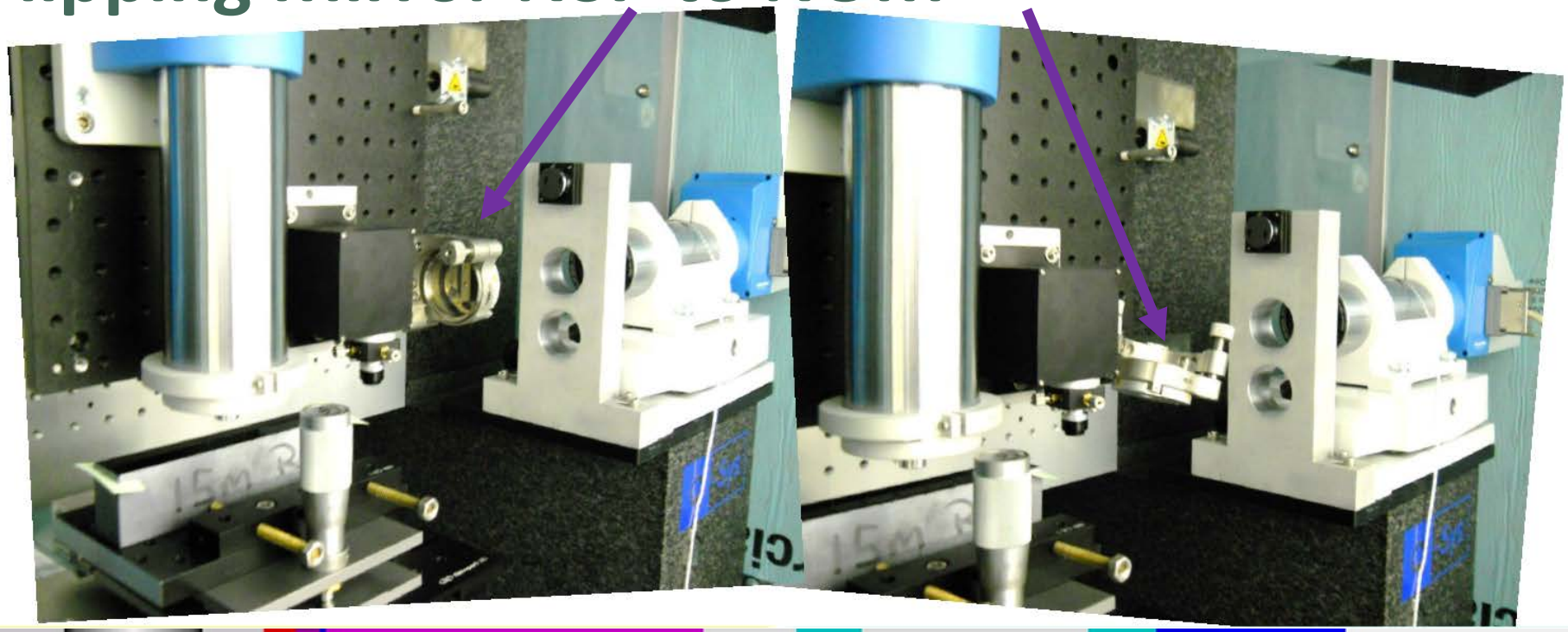




Deflectometry based Optical Metrology Station

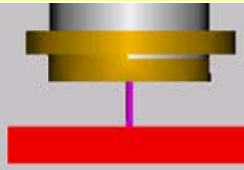
Nano Surface Profiler : NSP *(Shinan Qian – Bo Gao)*

Flipping Mirror NSP to NOM



Elcomat / 8

Easy switching between **NSP** and BNL-**NOM**



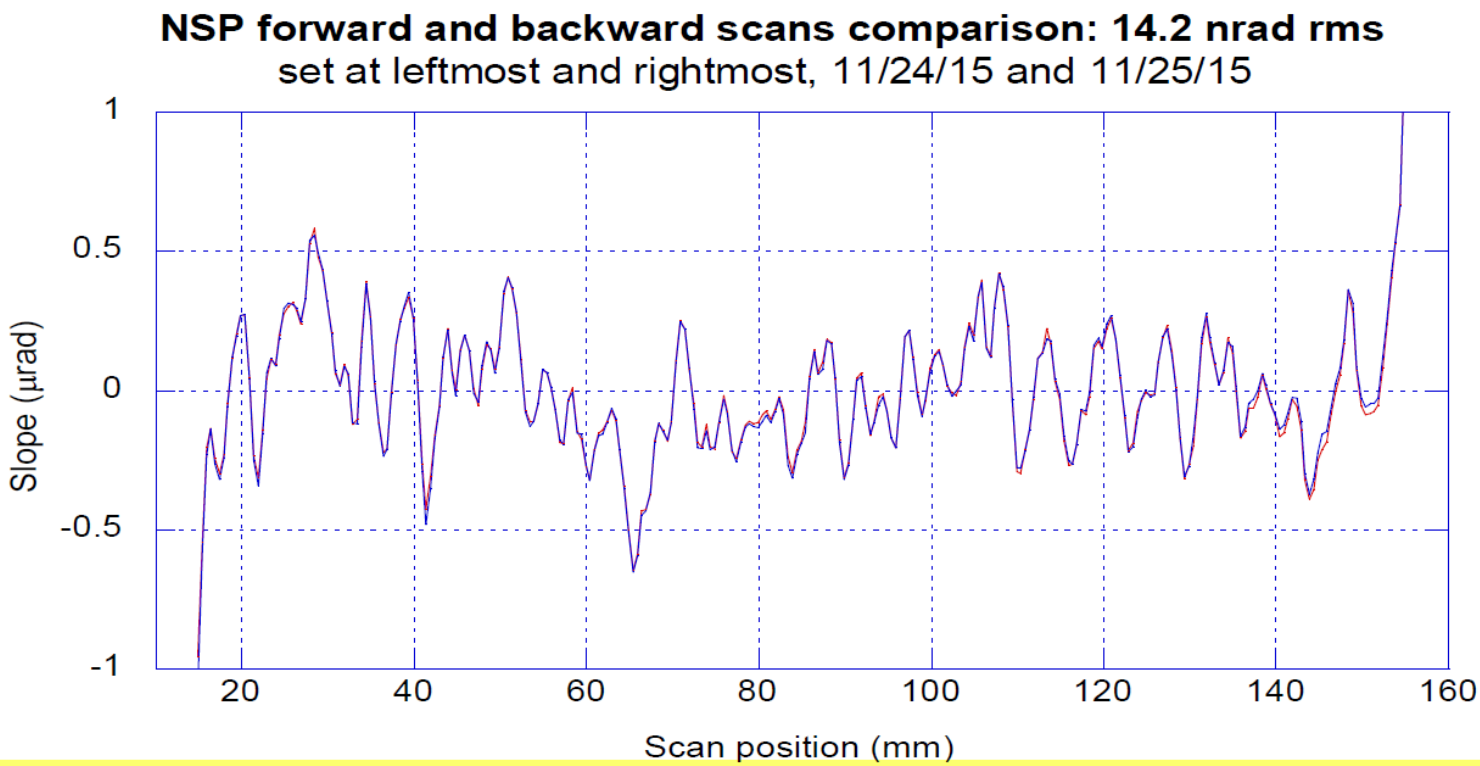
FIXED SAMPLING DISTANCE (2.5 mm)

Deflectometry based Optical Metrology Station

Nano Surface Profiler : NSP

Self-comparison test of the **NSP** on plane mirror M#1: FW - BW scans

Mirror is tested at leftmost and rightmost in a distance of **800 mm**
The difference is 14.2 nrad rms



An excellent repeatability

R&D Directions

New Metrology tools

- *Try to reach the 50 nrad rms level for CURVED Mirrors*

At Wavelength Metrology

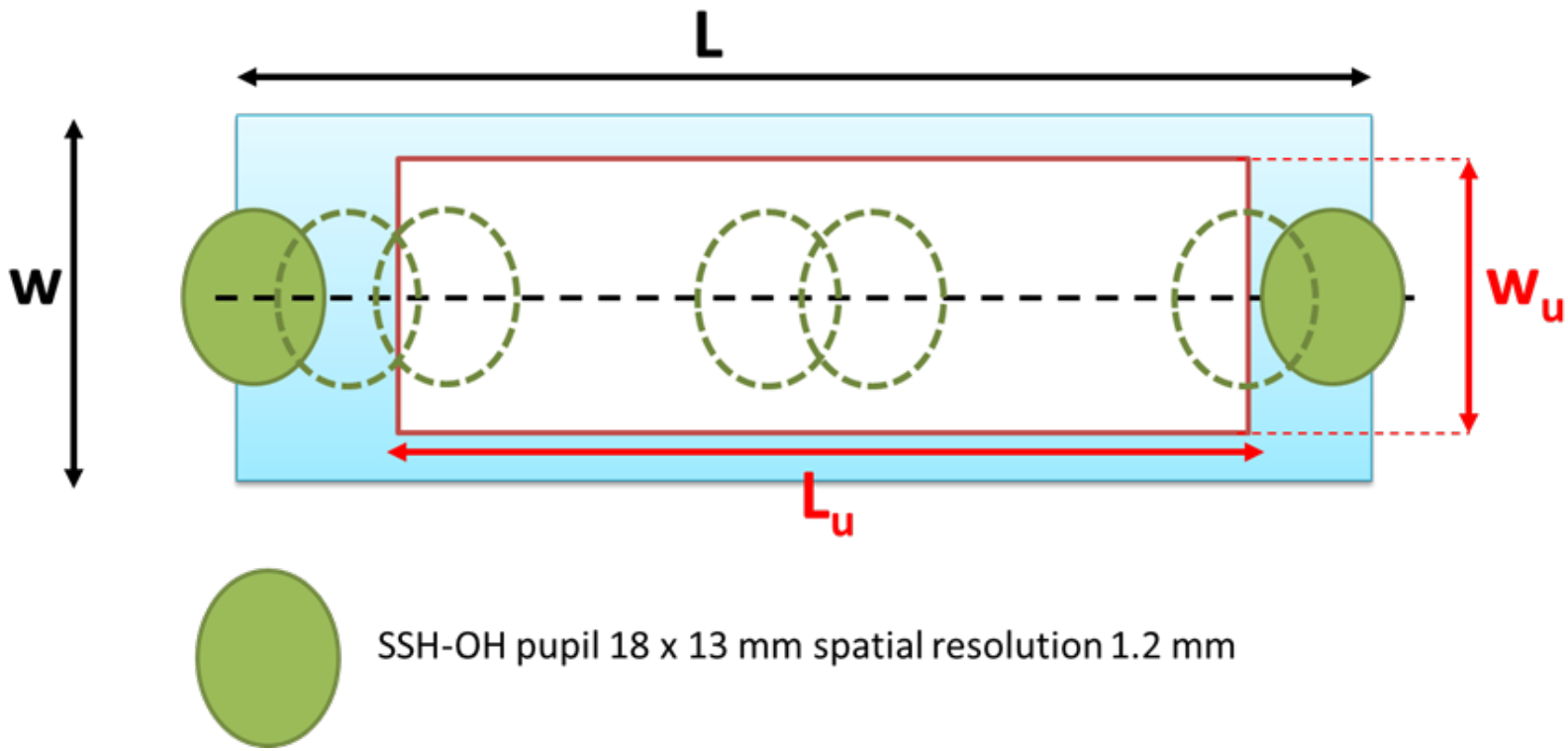
- *Try to develop wavefront analysis for*
  - *Optics Alignment*
  - *X-ray Active Optics*
  - *X-ray Imaging*

Deterministic Polishing

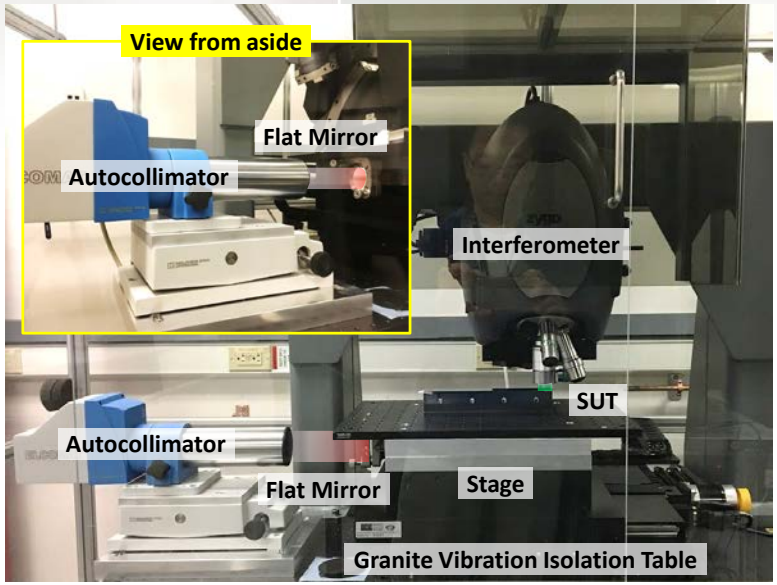
- *Try to "produce" state of the art mirrors*

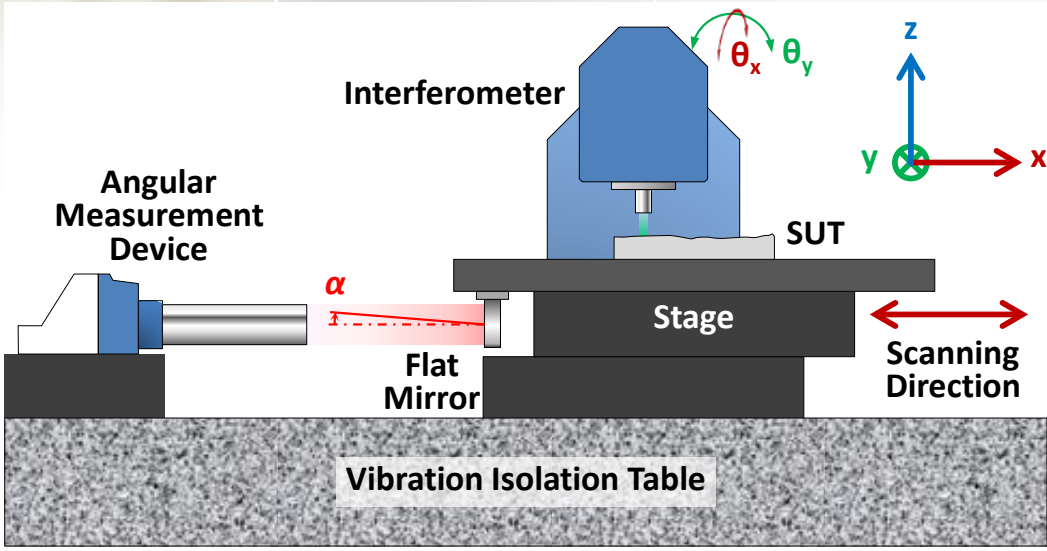
TEST Beamline

Stitching principle



Stitching Interferometry





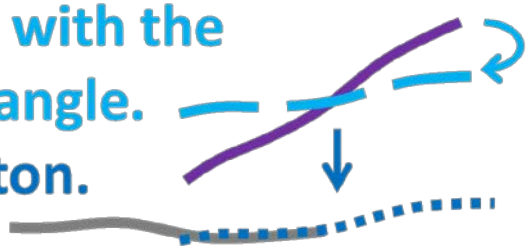
Stitching procedures:

0) Measure the tilt angle.

$$t = -\tan(\alpha)$$

1) Correct tilt with the measured angle.

2) Adjust piston.

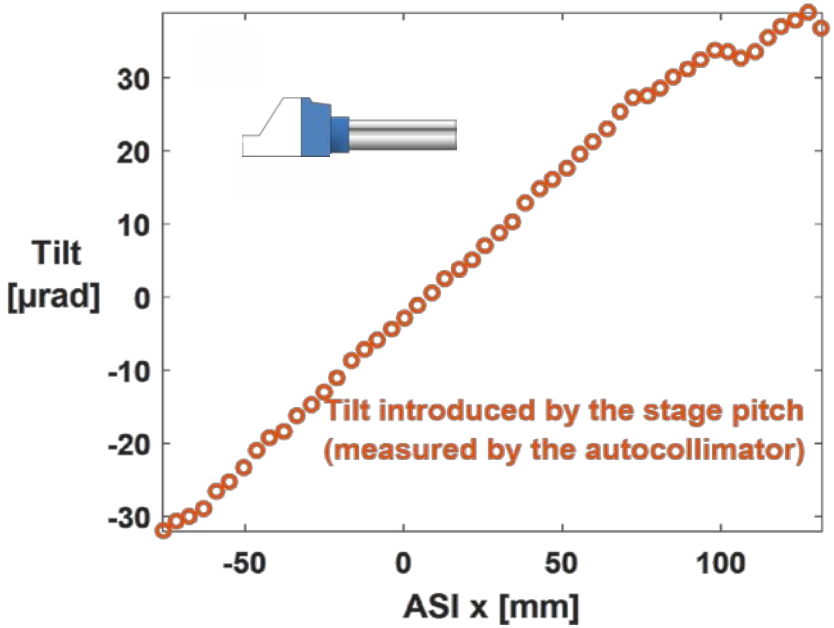


$$h_n(x) = \varphi_n(x) - t_n \cdot x$$

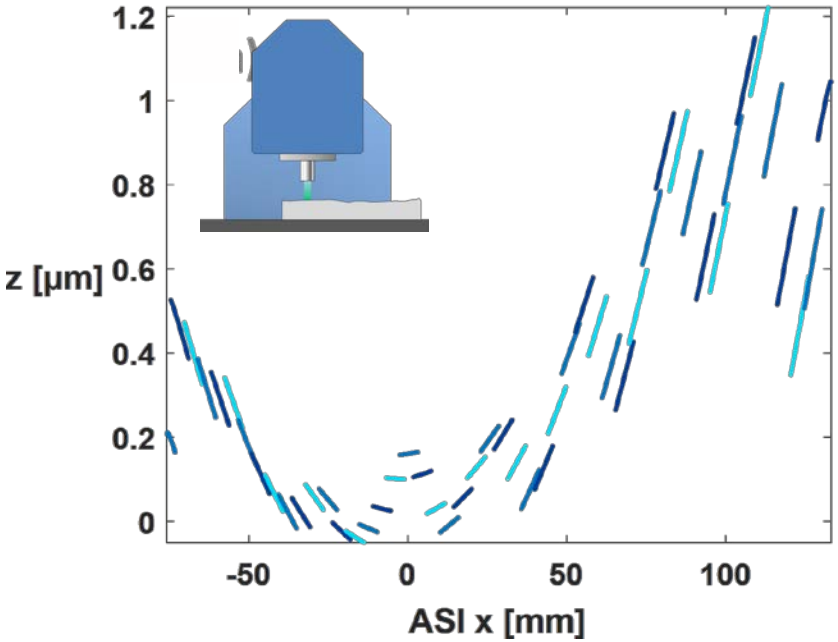
$$z_n(x) = h_n(x) + \overline{\Delta h_n}$$

1st Test: flat mirrors

AC measures the tilt angle of the stage at each scanning step.



WLI measures the local profile

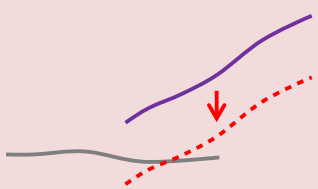


Three way to analyse the data

A

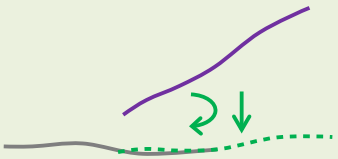
Stage Trusting Stitching

$t_n = 0$



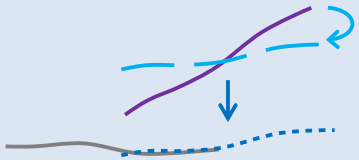
B

Classical Software Stitching



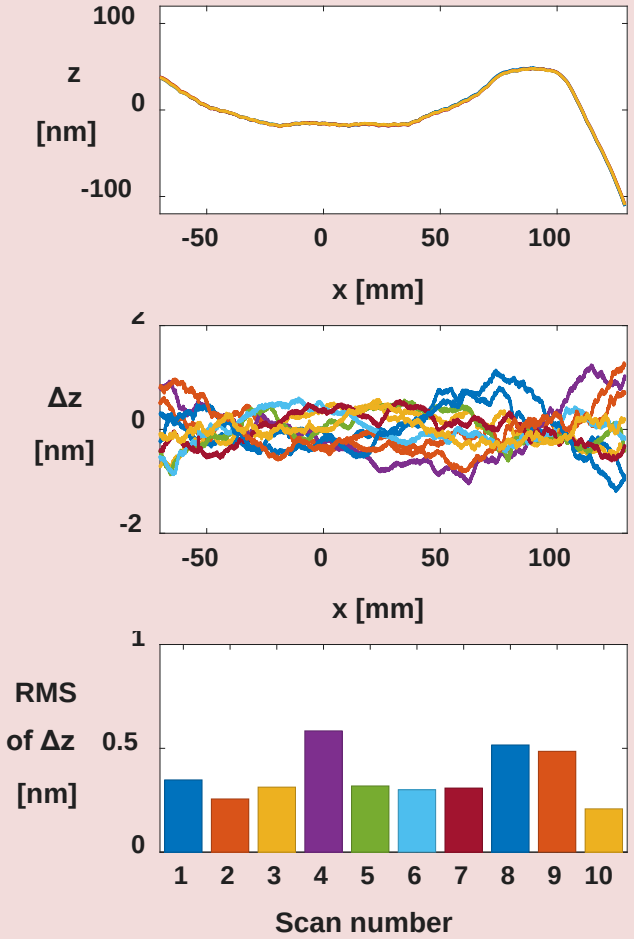
C

Angle Measuring Stitching

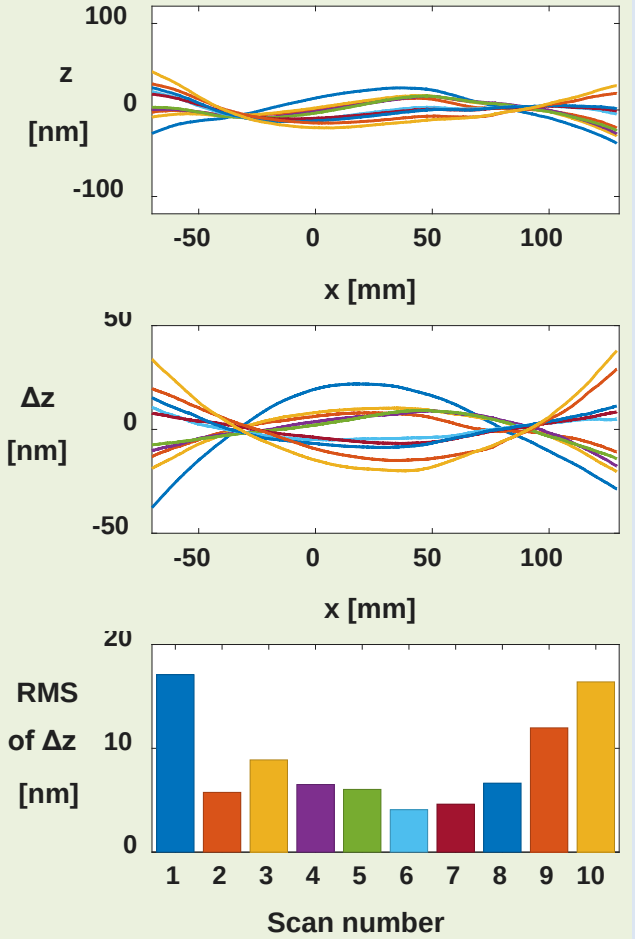


A B C

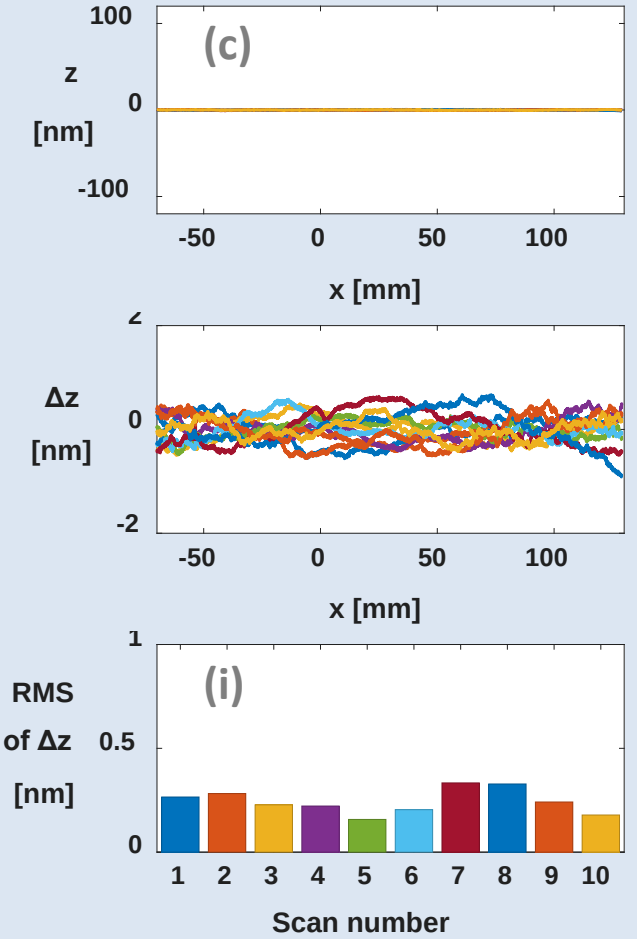
Stage Trusting Stitching



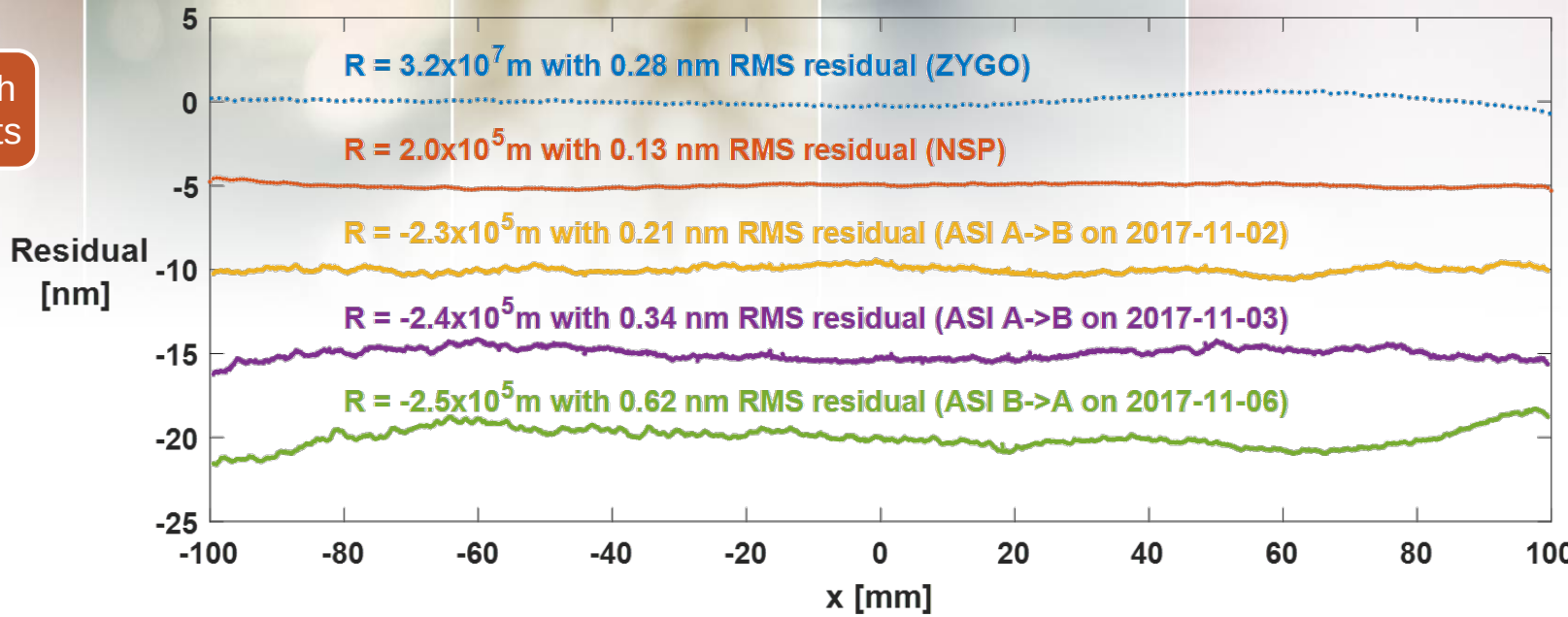
Classical Software Stitching



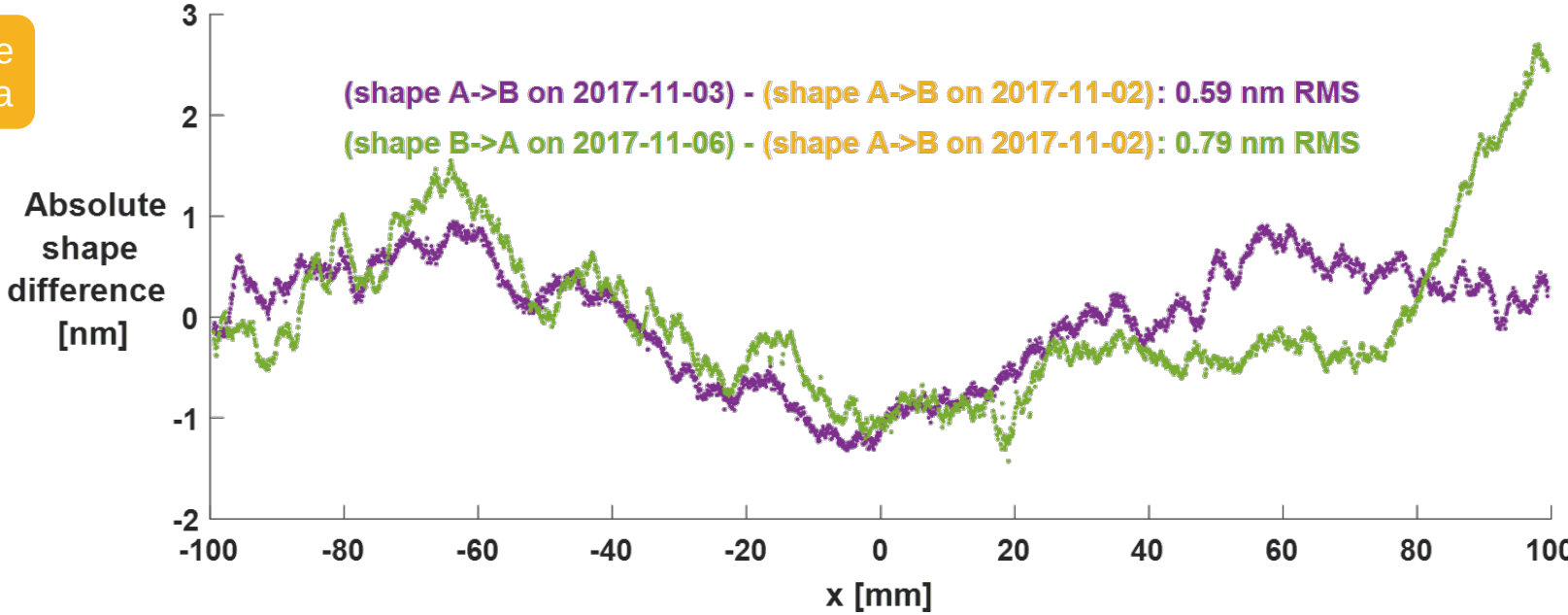
Angle Measuring Stitching



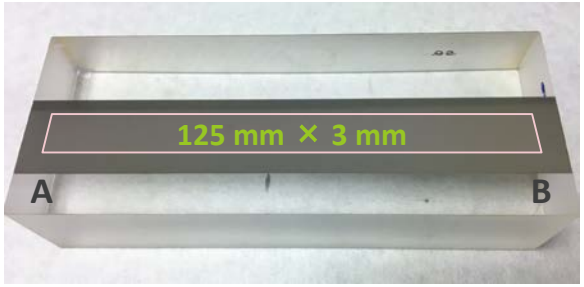
Comparison with other instruments

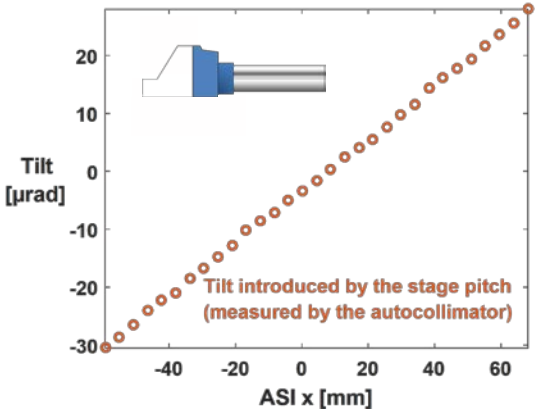


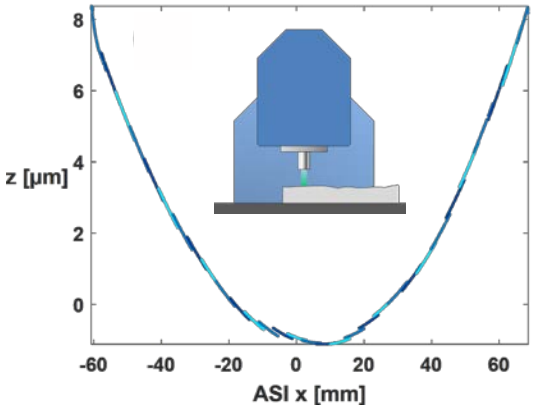
Difference of the reproduced data



Measurement: Elliptical cylindrical mirror

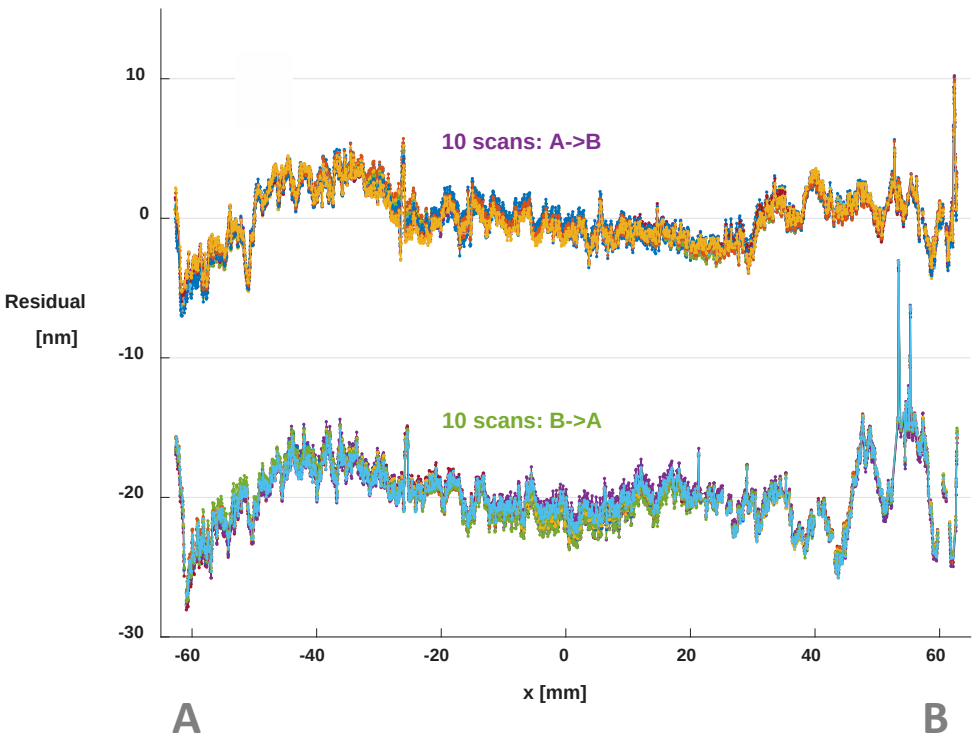


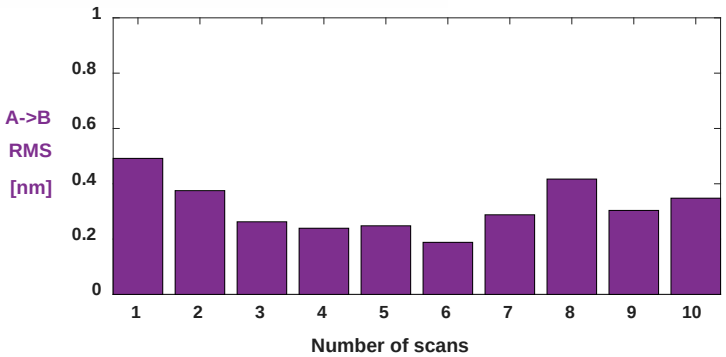


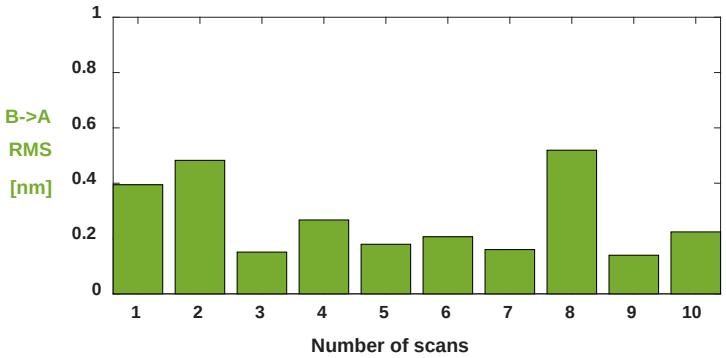


Parameters of the target ellipse	
Source-to-mirror distance	$p = 45.170\ [m]$
Mirror-to-focus distance	$q = 331.92\ [mm]$
Grazing angle	$\theta = 2.8\ [mrad]$

Repeatability

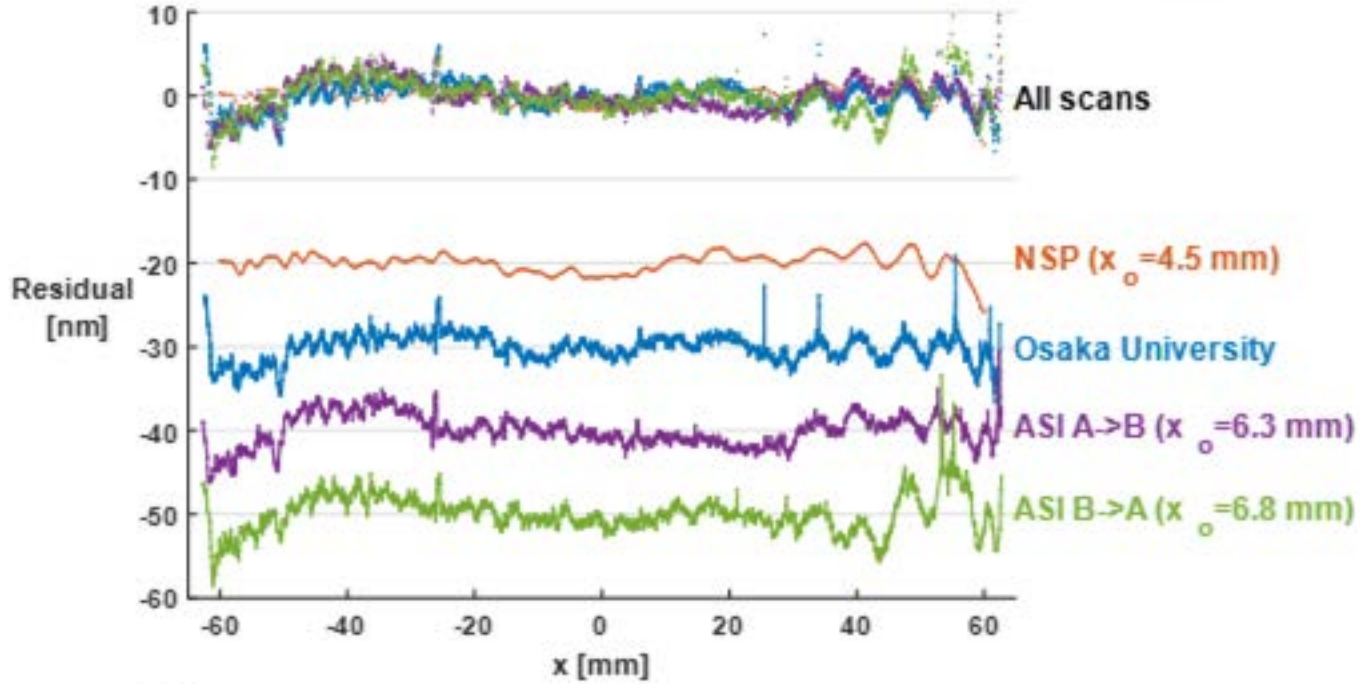




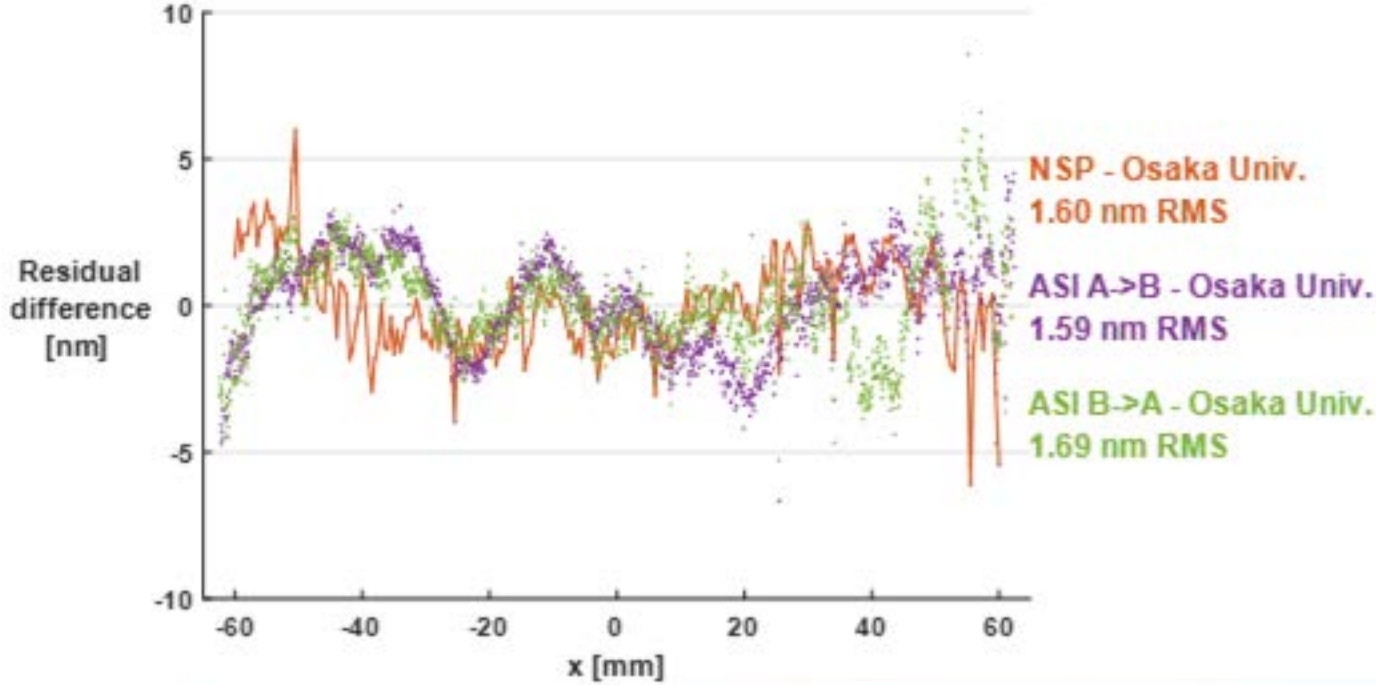


Comparison with other instruments

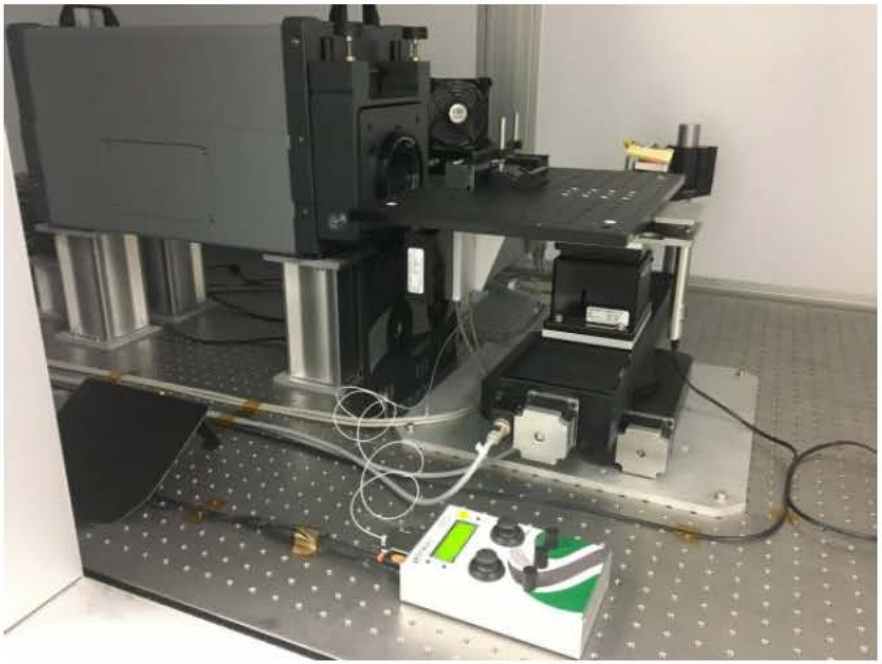
Reproducibility study

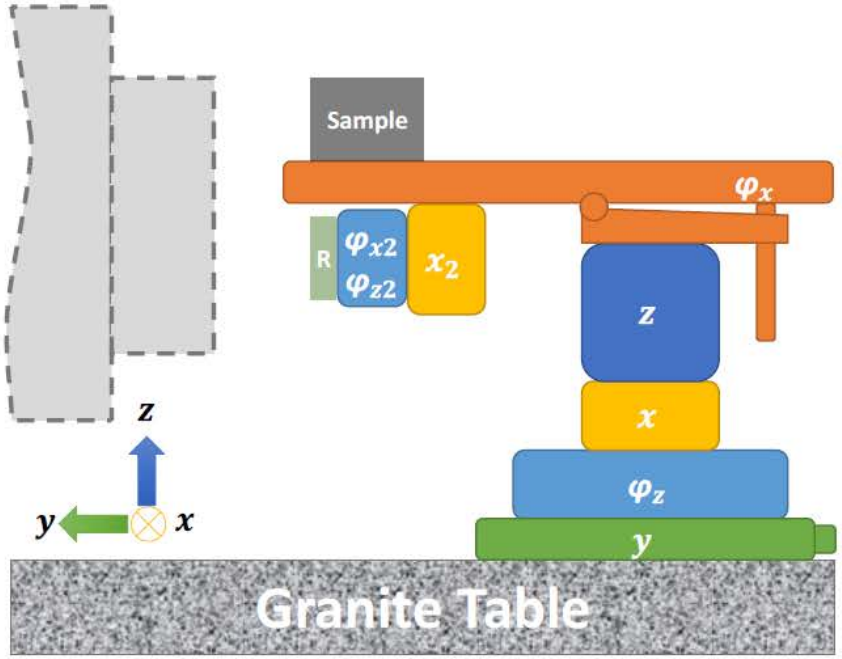


Difference from Osaka Univ. data

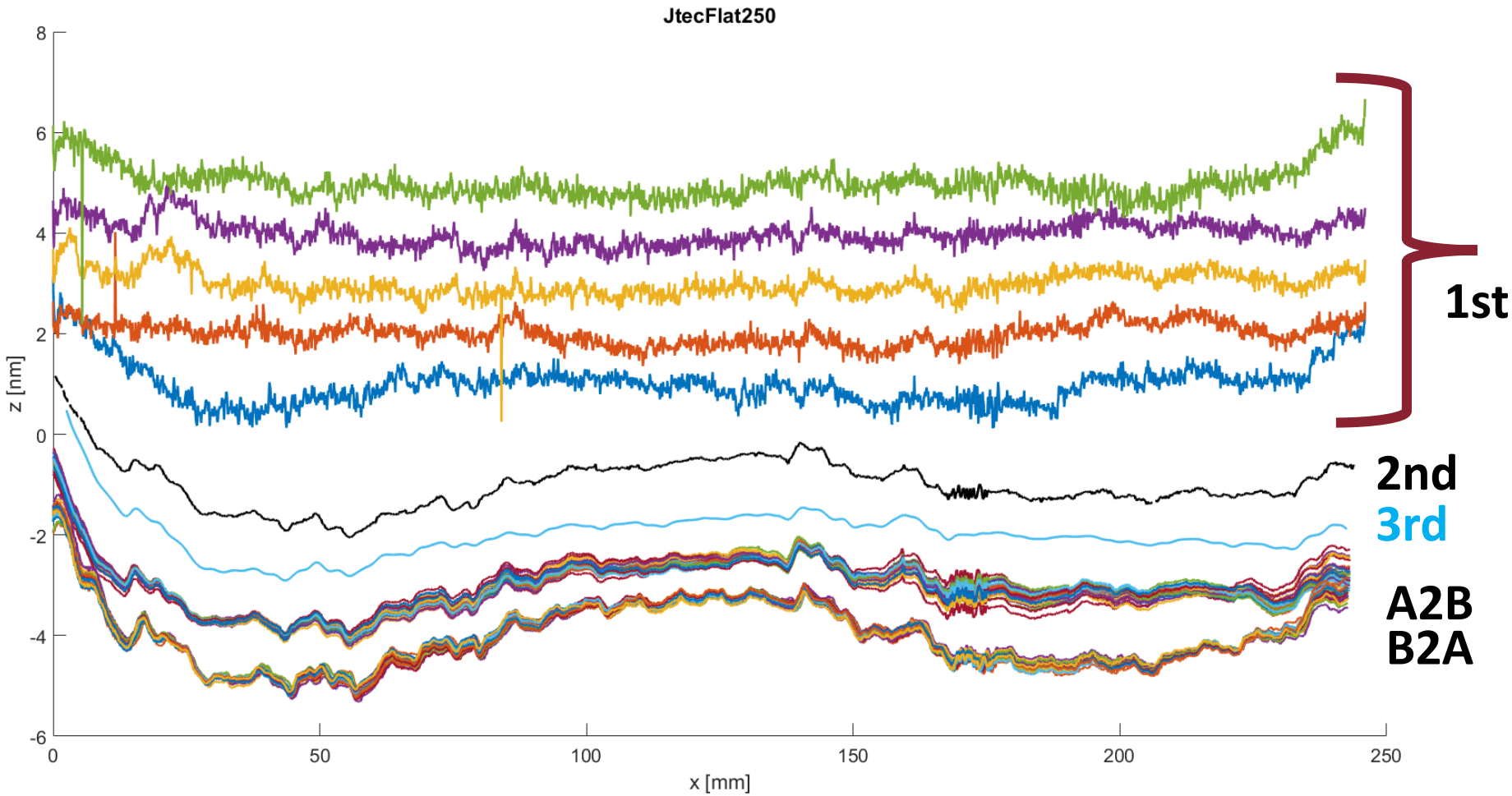


Stitching Interferometry



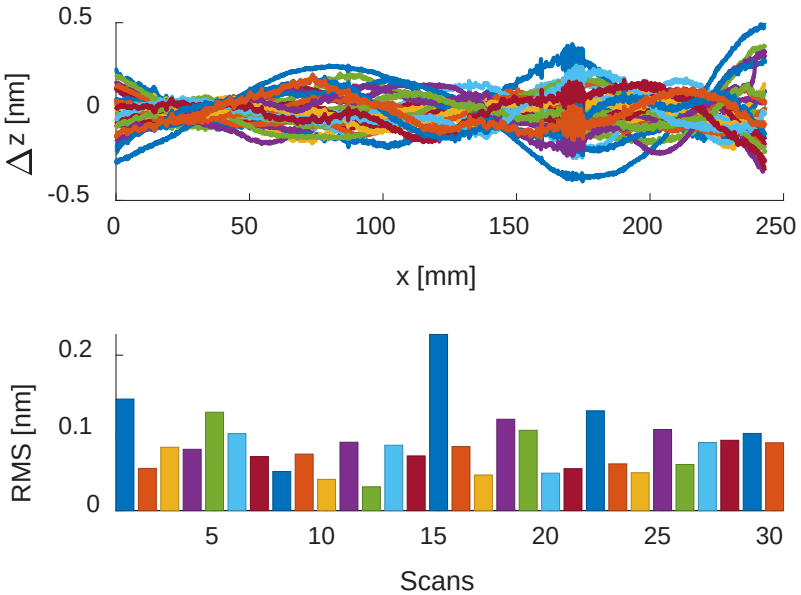


Stitching Interferometry

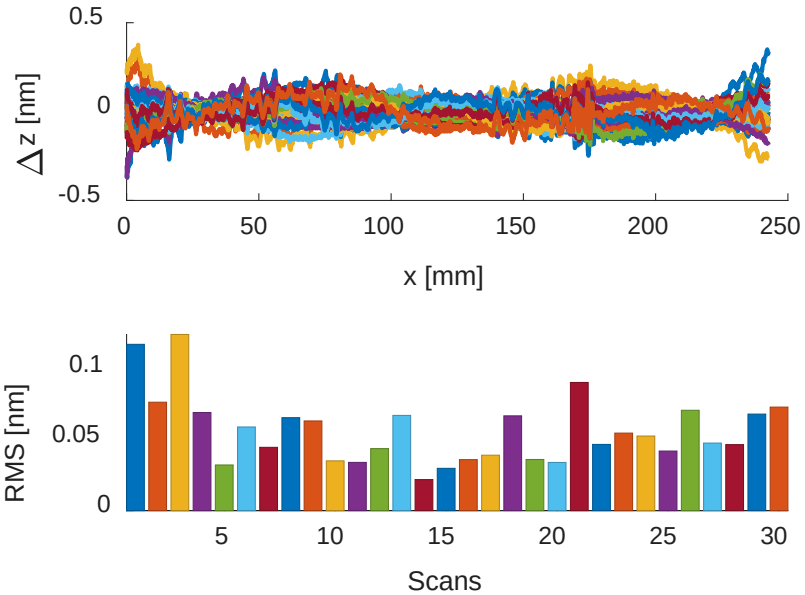


Stitching Interferometry

A2B 600x150 Repeatability

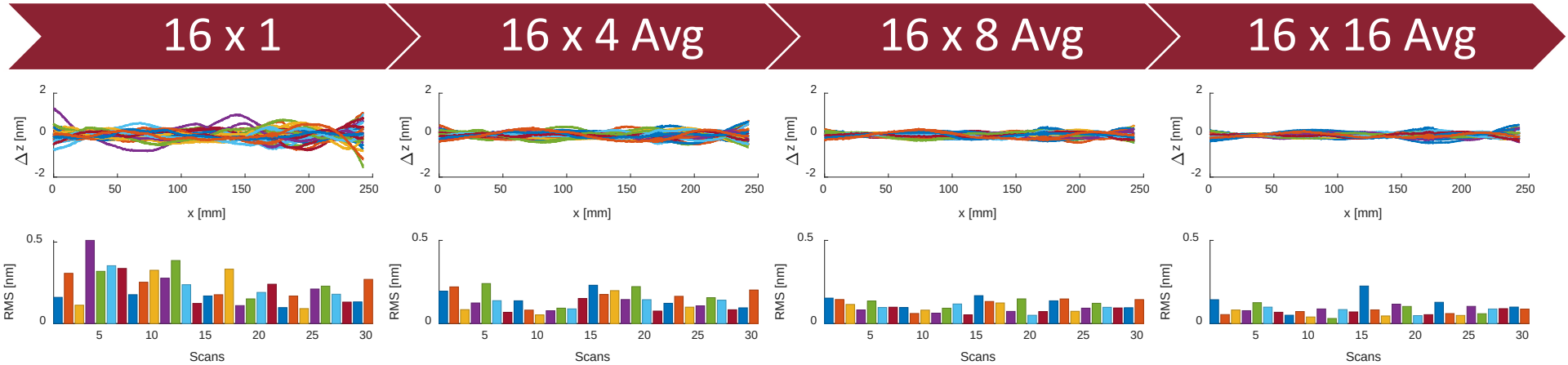


B2A 300x60 Repeatability

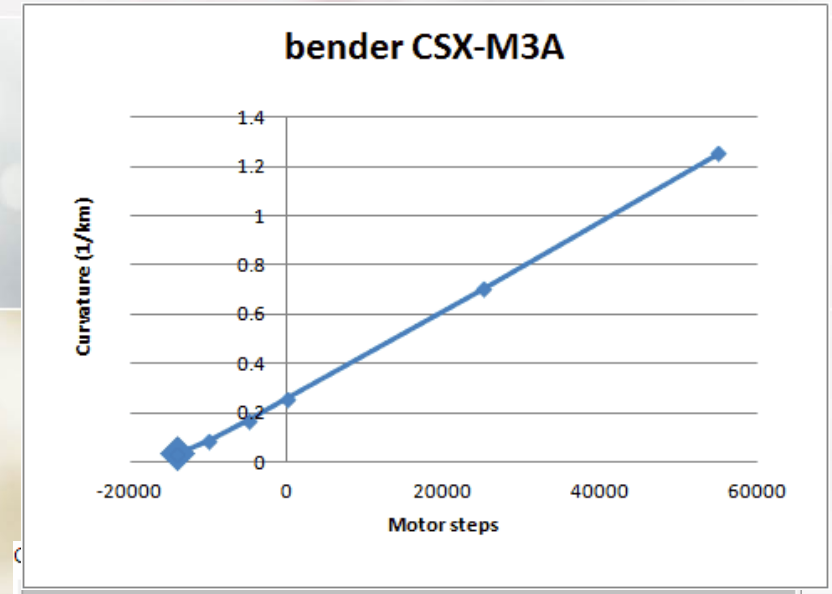


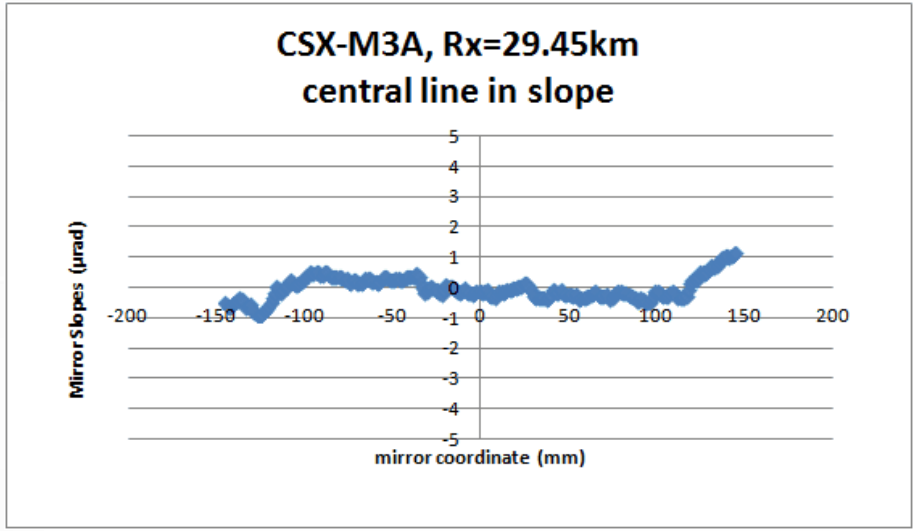
Stitching Interferometry

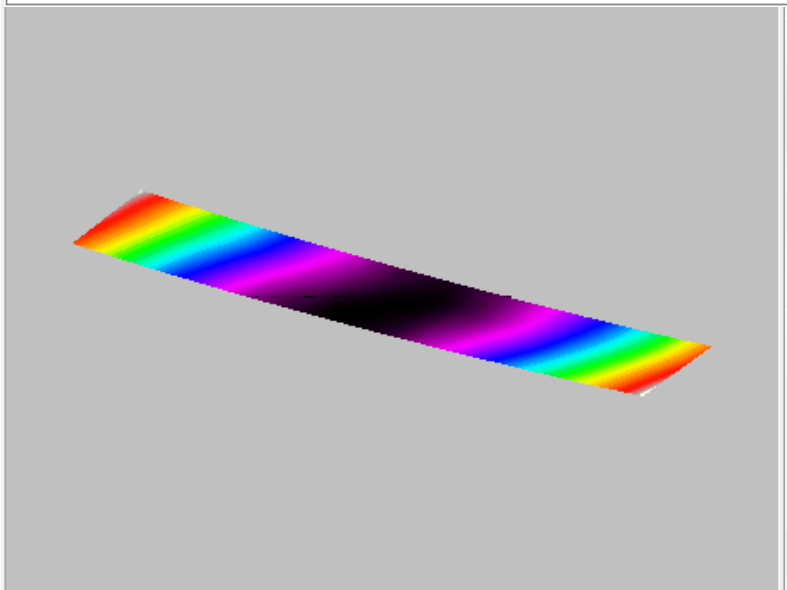
Repeatability under different average settings

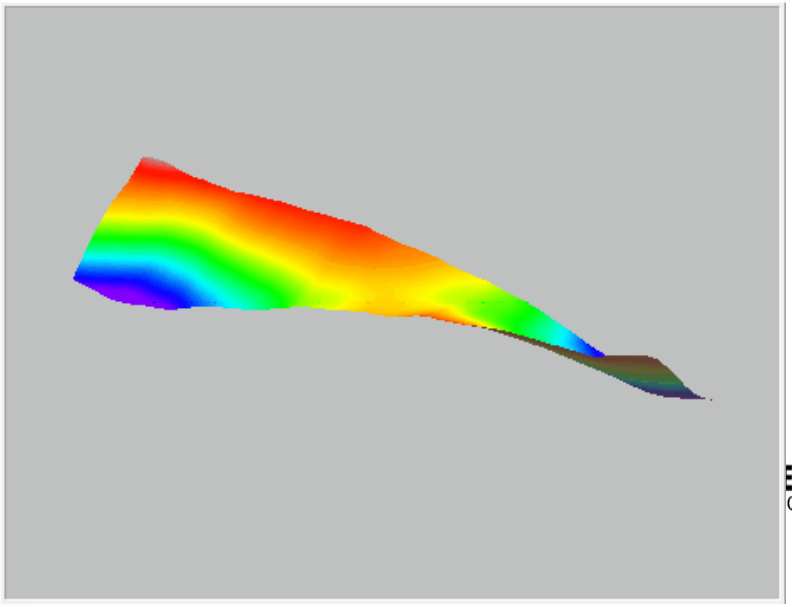


Why do we need 2D information?



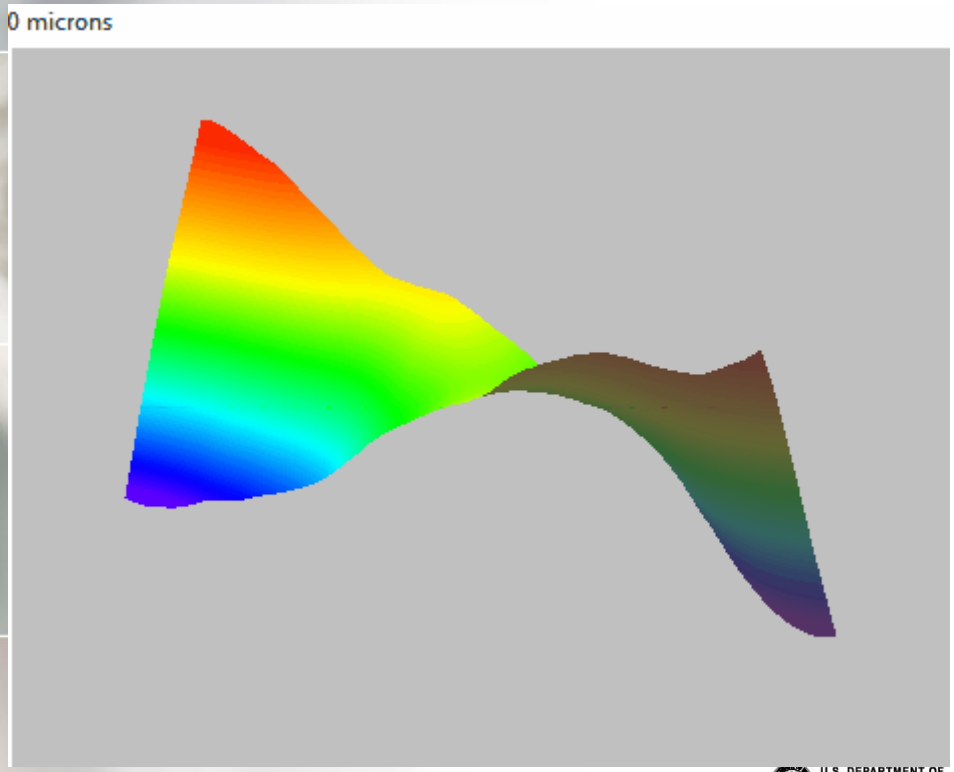






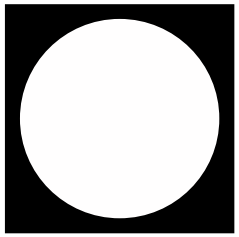
Why do we need 2D information

Bendable mirror

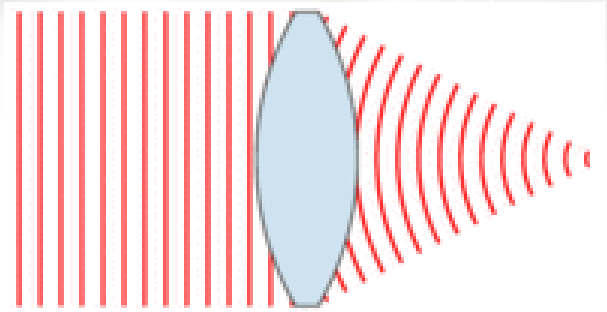


Wavefront : At λ Metrology

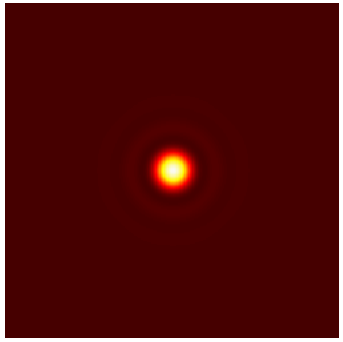
$a(\vec{r})$



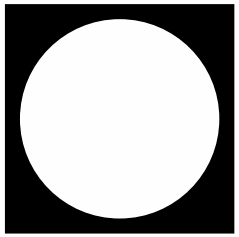
$\delta(\vec{r})$



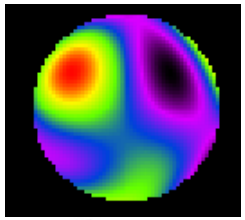
Propagation



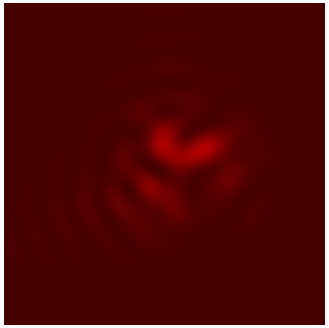
$a(\vec{r})$



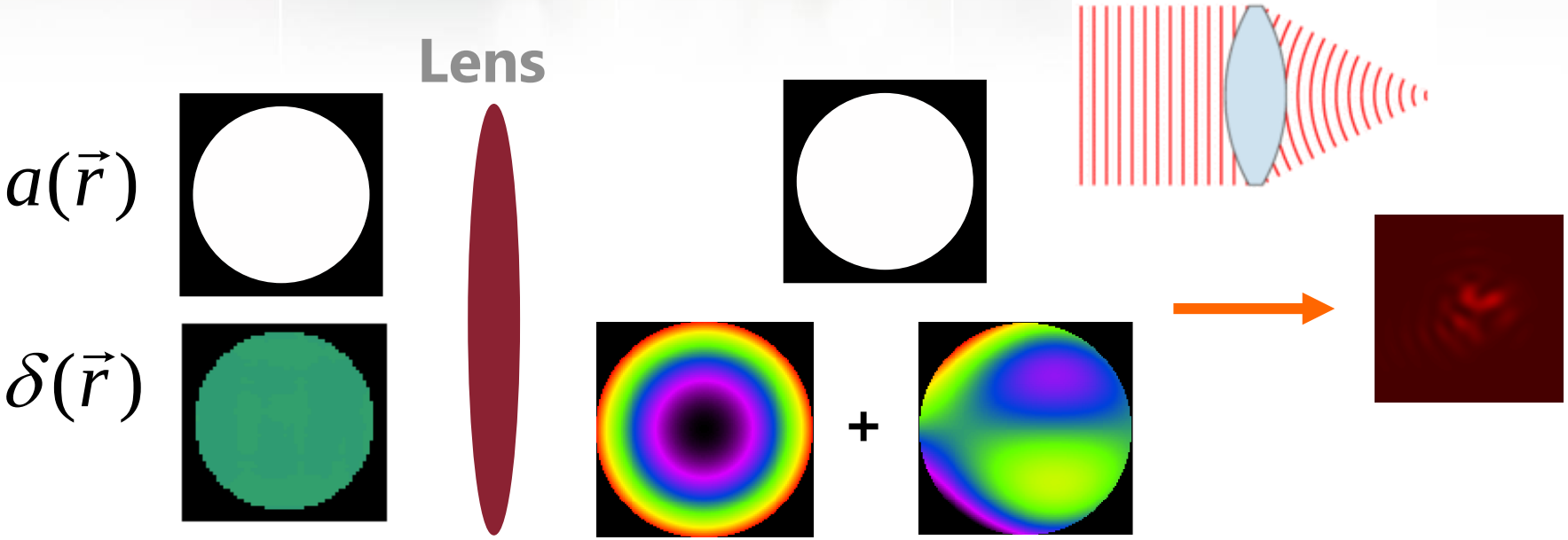
$\delta(\vec{r})$



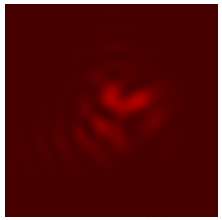
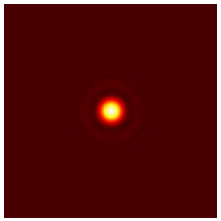
Propagation



The PSF and Strehl Ratio



The intensity profile at focus is the **Point Spread Function**

Max  / Max  = **Strehl Ratio**

Looking only and the intensity can sometimes misinterpret the reality

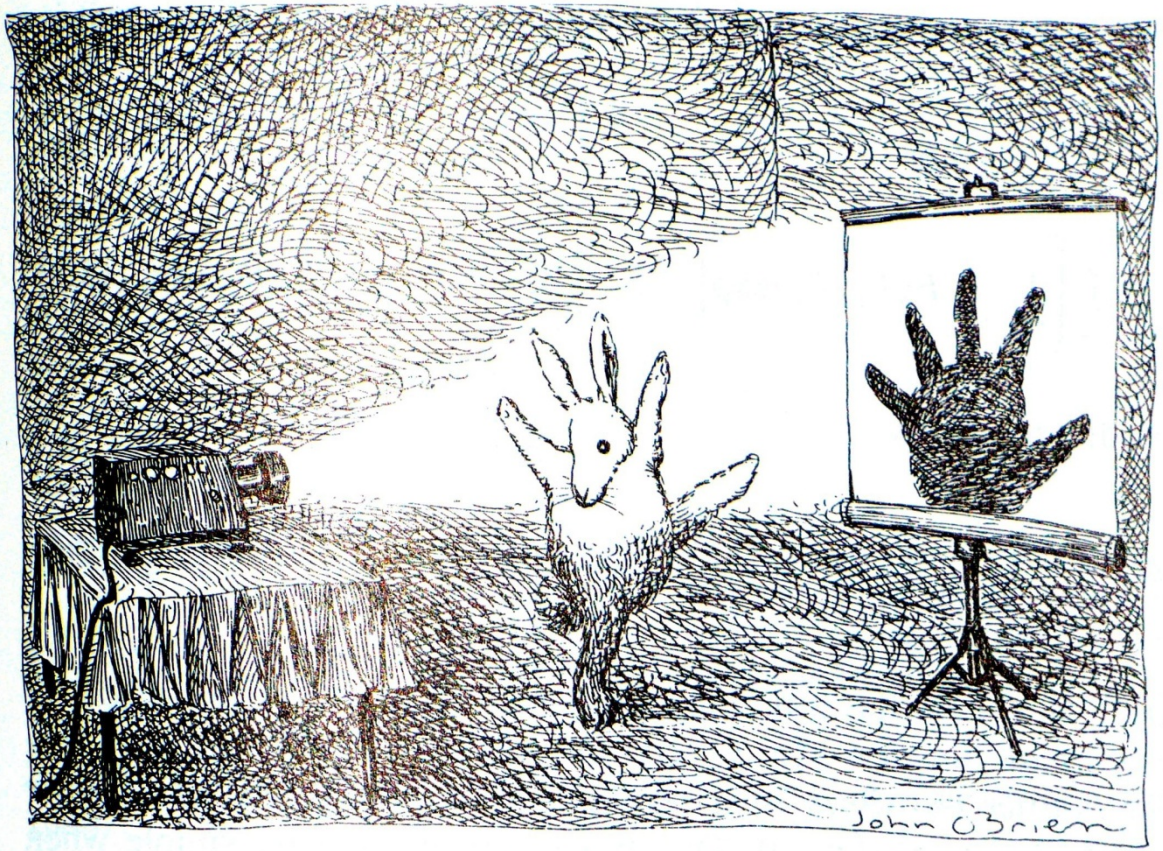
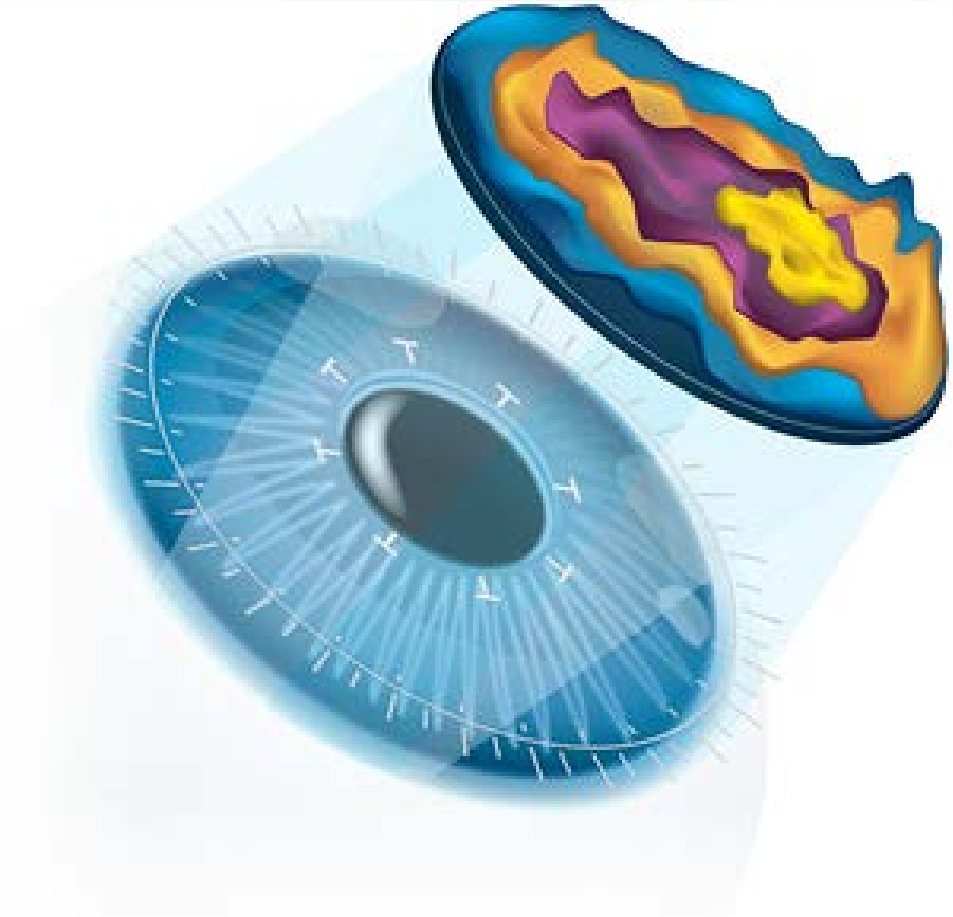


Fig. 5.1. A single projection image is plainly insufficient to infer the structure of an object. Drawing by John O'Brien; © 1991 The New Yorker Magazine.

Wavefront : At λ Metrology



Surgery

Lenses or Glasses

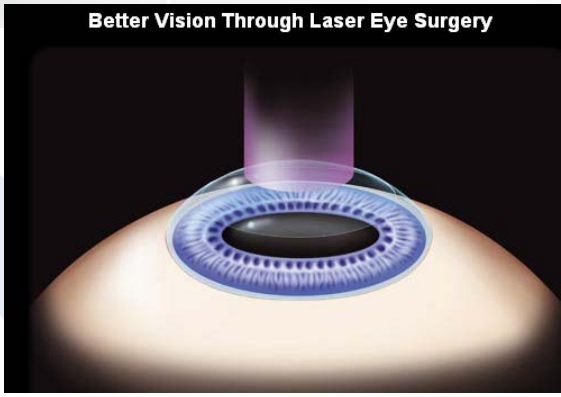
Wavefront-guided LASIK = Surgery

LASIK Laser-Assisted in SItu Keratomileusis

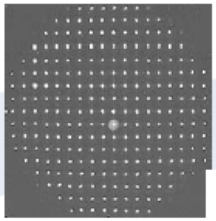
Wavefront-guided LASIK is a variation of LASIK surgery in which, rather than applying a simple correction of only long/short-sightedness and astigmatism (only lower order aberrations as in traditional LASIK), an ophthalmologist applies a spatially varying correction, guiding the computer-controlled excimer laser with measurements from a wavefront sensor. The goal is to achieve a more optically perfect eye.

Wikipedia

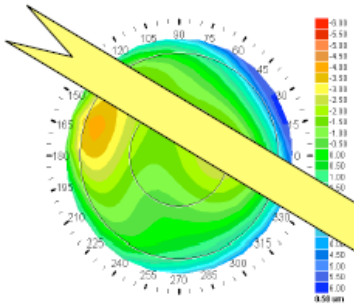
Wavefront-guided LASIK



The problem

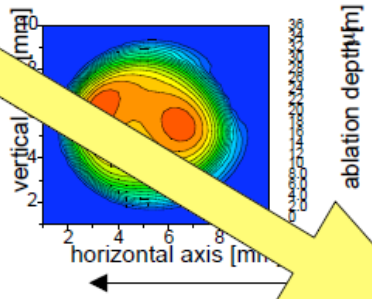


Aberration measurements

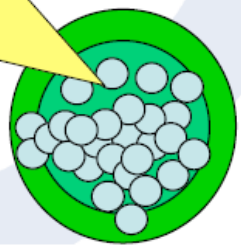


Wavefront reconstruction

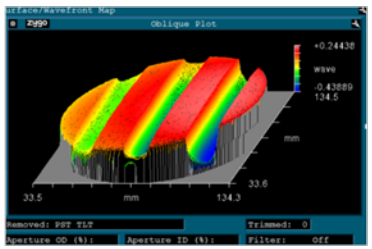
Ablation profile calculations

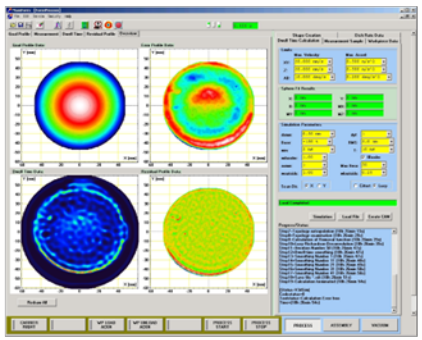


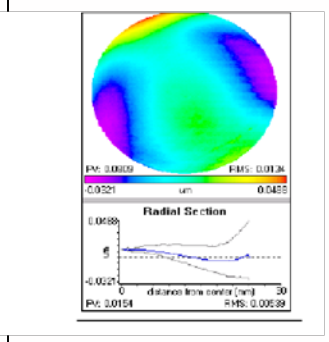
spot calculations & ablation



Ion Beam Polishing
Step by Step

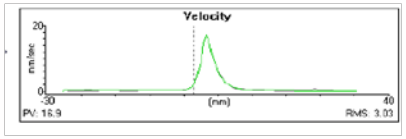




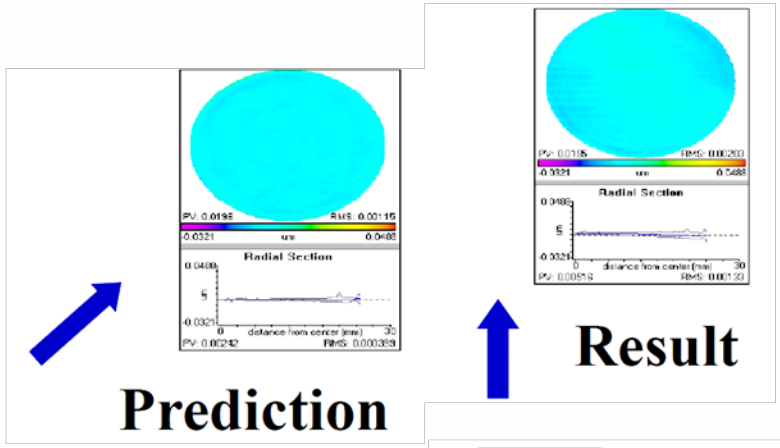


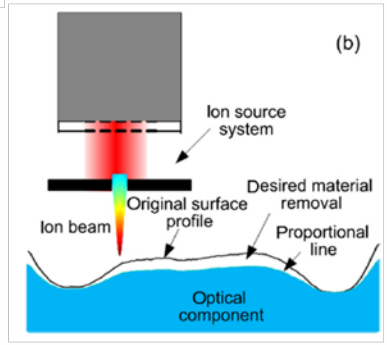
Measurement

Calculation



Process Code Generation

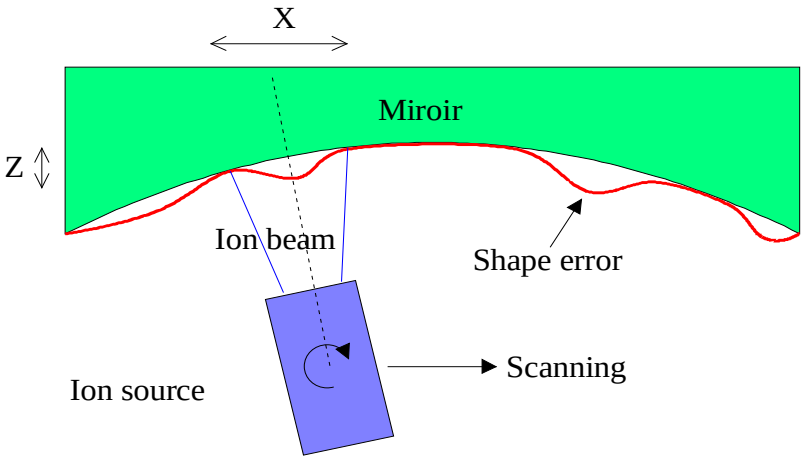




Process

Internal NSLS II Collaboration : optical Metrology and Optical Fabrication Groups

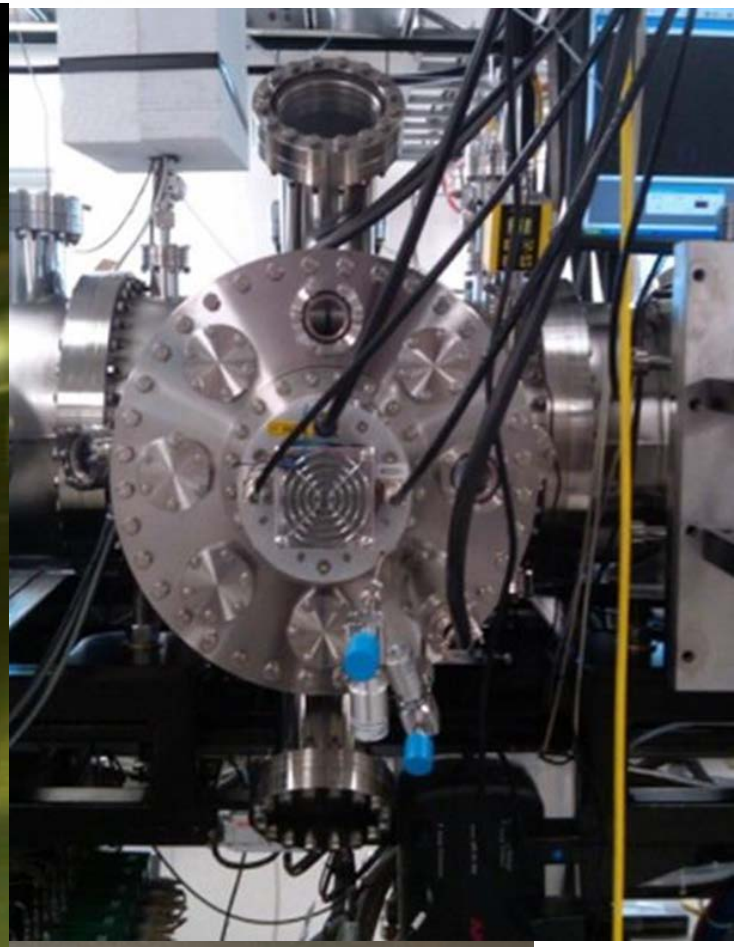
Ion Beam Figuring (IBF)



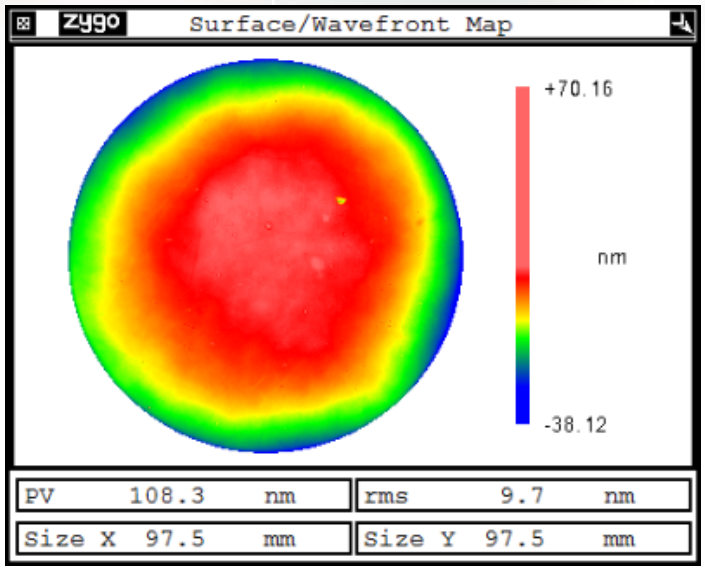
- Last step in figuring/polishing process of optics
- Sputtering of unwanted material
- Correction of long spatial wavelengths (X ~ cm)
- Correction of small thickness (Z < μm)

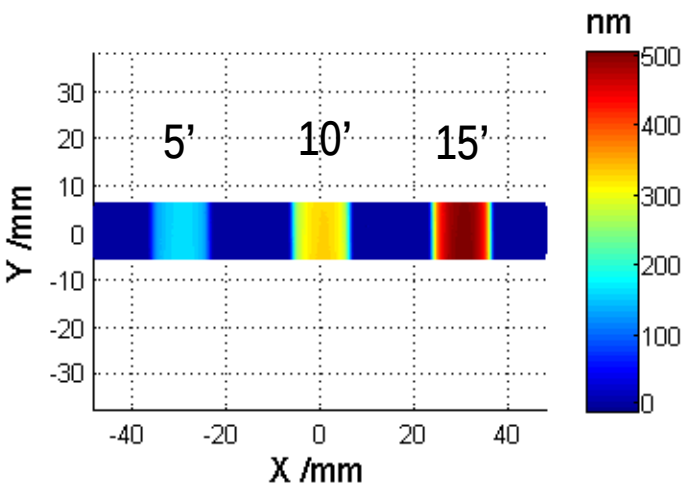
Internal NSLS II Collaboration : optical Metrology and Optical Fabrication Groups

Ion Beam Figuring (IBF)

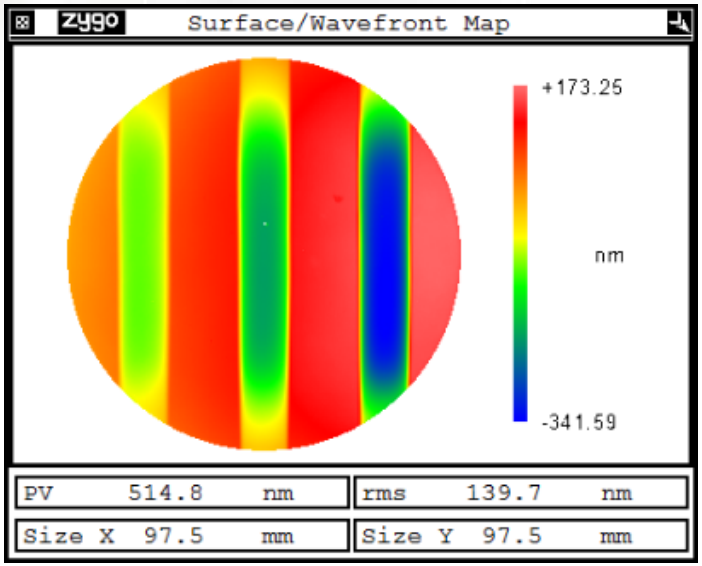


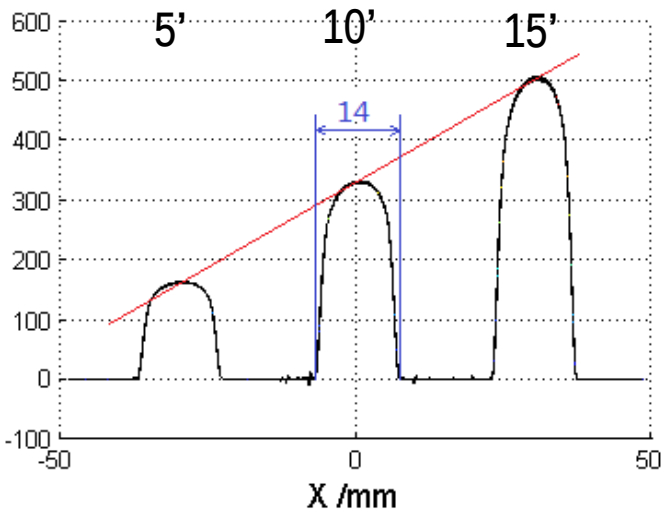
Before IBF





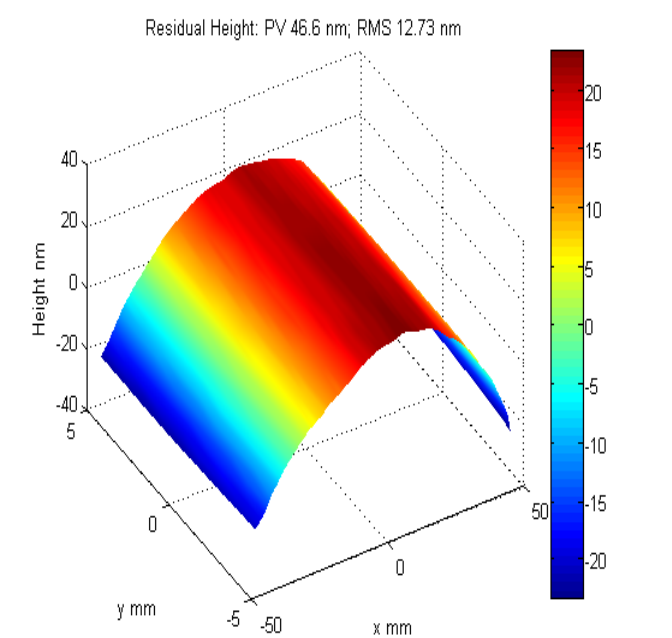
After IBF





Ion Beam Figuring – Flat Sample - 1st run (9 minutes)

Plane sample #1

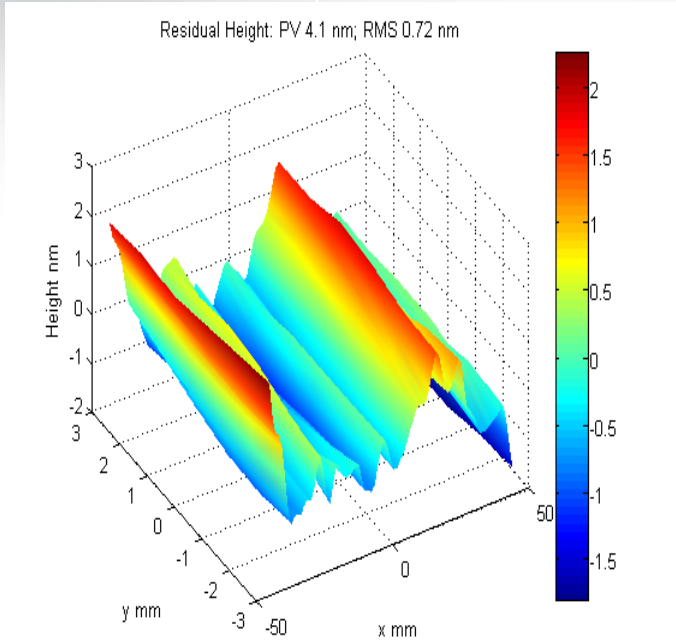


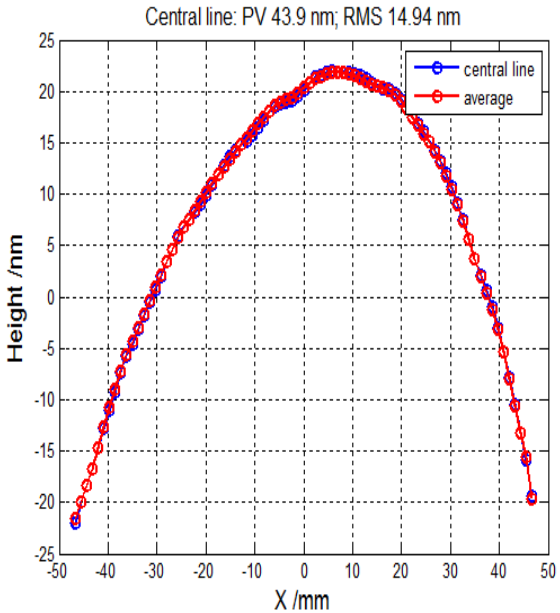
λ/14 ~ 300$

~ 44 nm PV
RMS: 15 nm

1D IBF

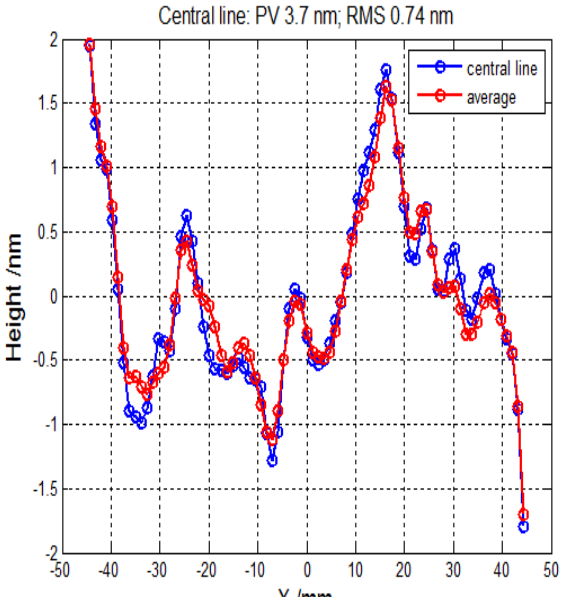
9 minutes



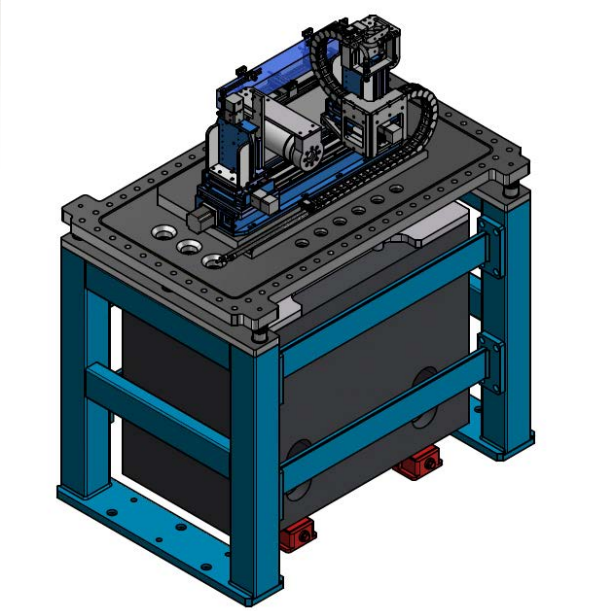


~ 3.7 nm PV
RMS: 0.74 nm

λ/171 ~ 3000$



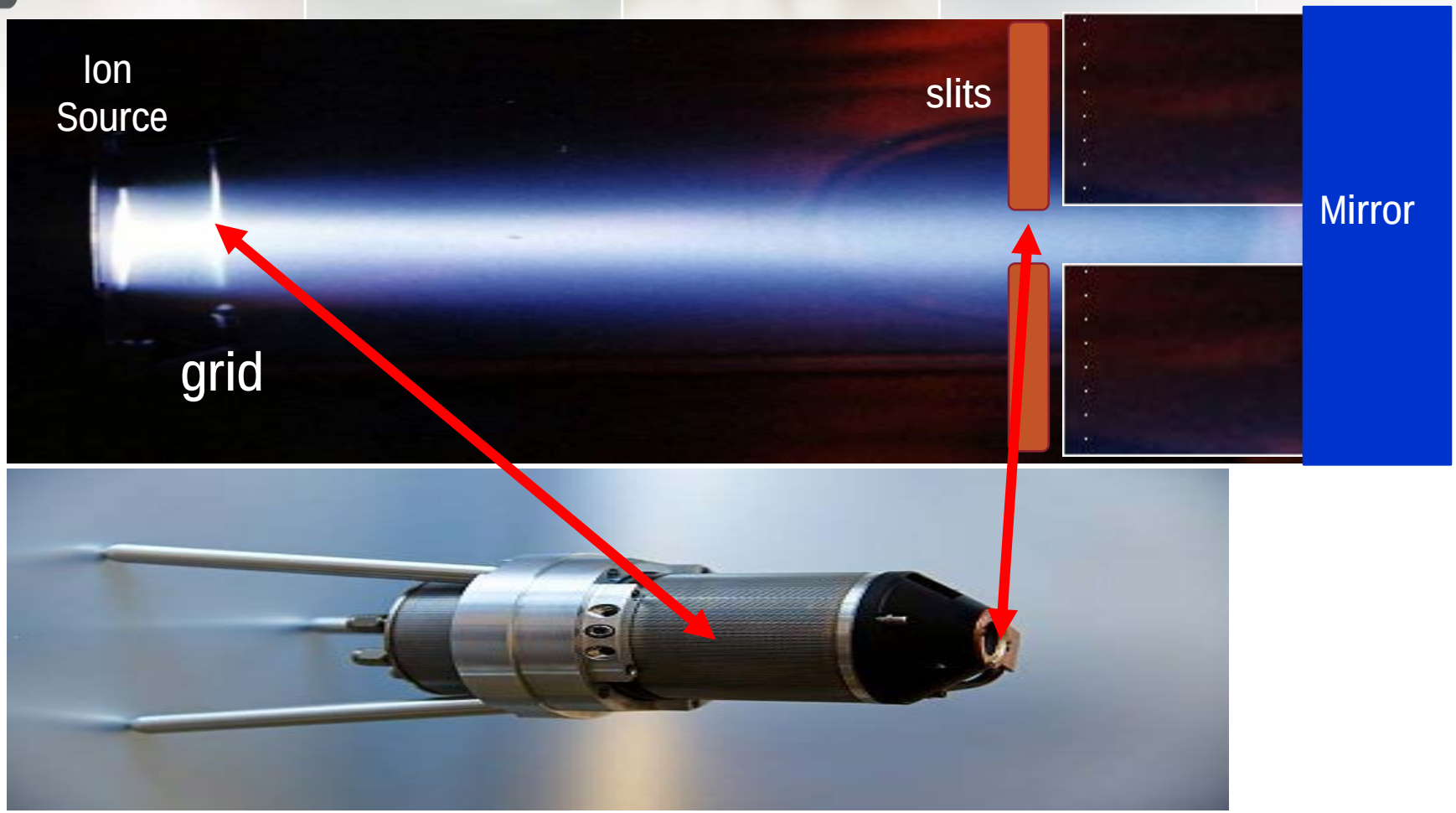
New IBF project



1. **Finish the Experimental Station**
2. **Test the adaptive Ion beam source prototype**
3. **“Produce” mirror prototype for NSLSII Beamline**

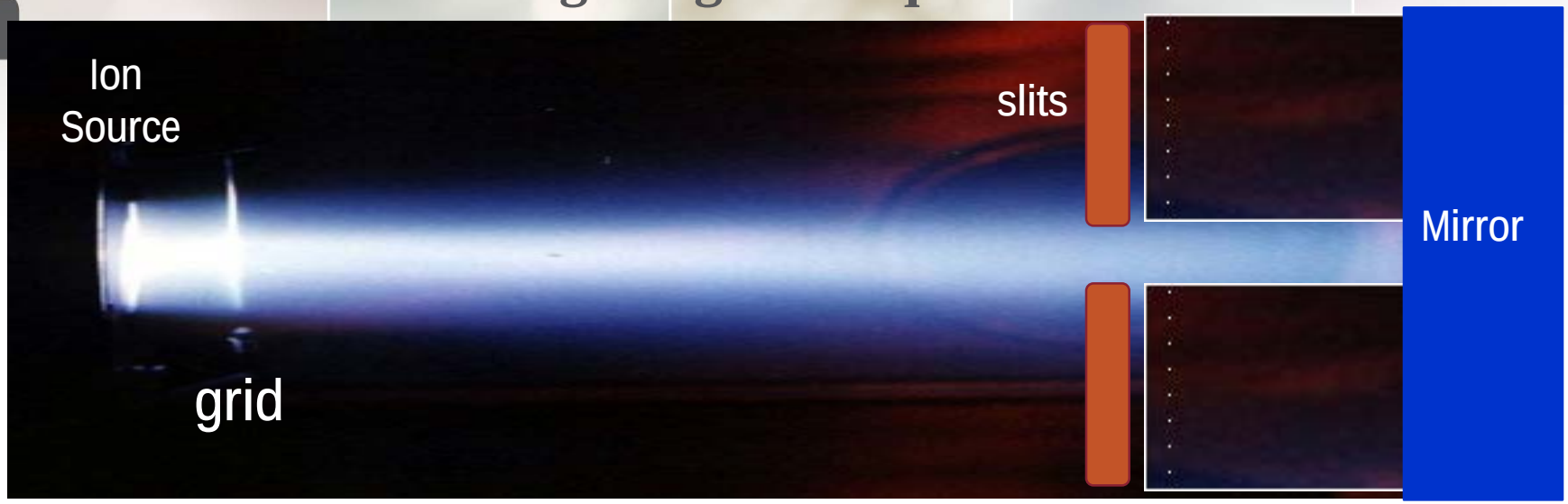
Discussion with US polishing companies

Classical Ion Beam Figuring technique : Ion Source + Grid + slits



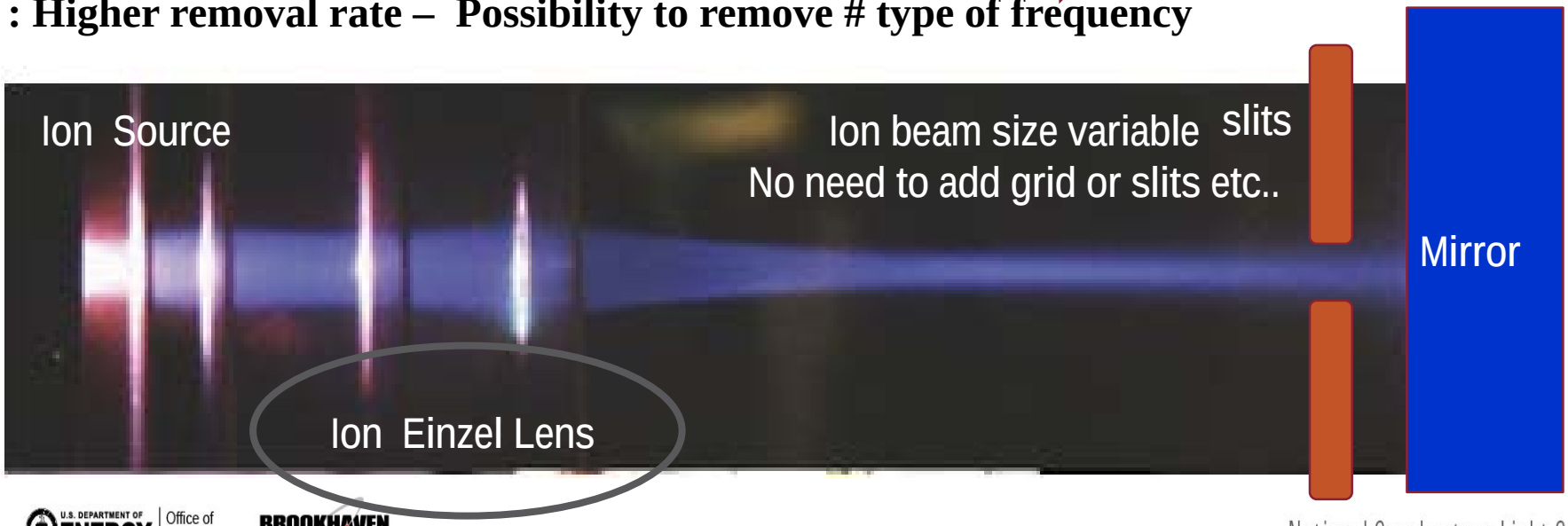
The ion source beam size or the pinhole size will determine the lowest frequency you can remove on the mirror surface

Classical Ion Beam Figuring technique : Ion Source + Grid + slits

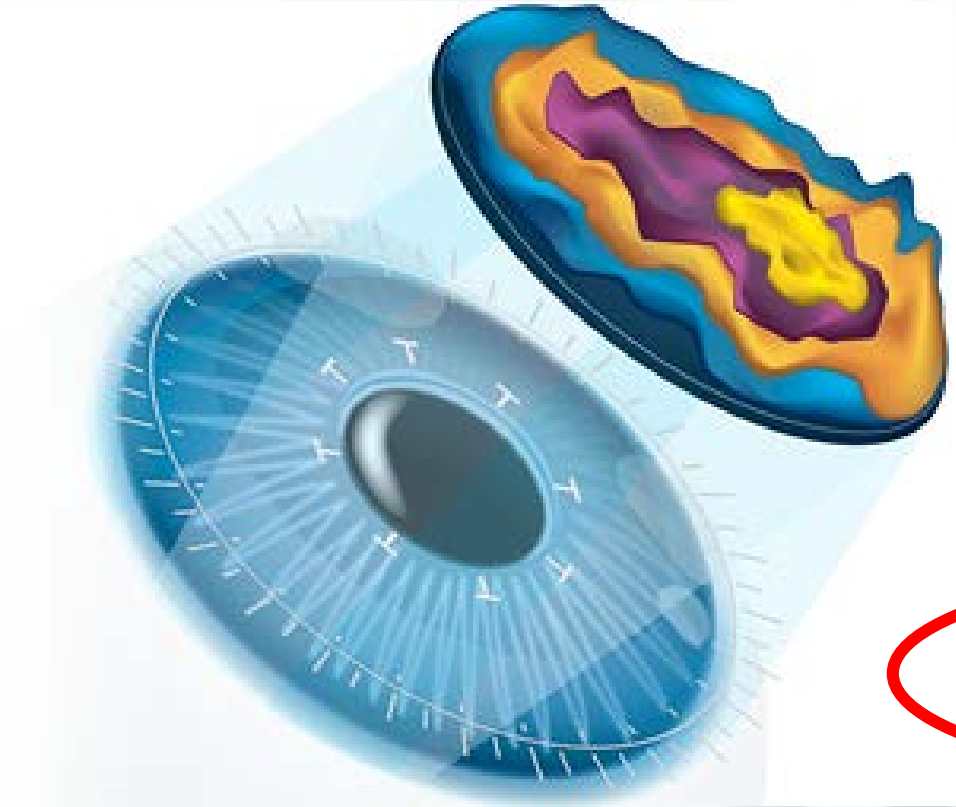


New Proposal : Ion Source + Einzel lens → Focus ion source

: Higher removal rate – Possibility to remove # type of frequency

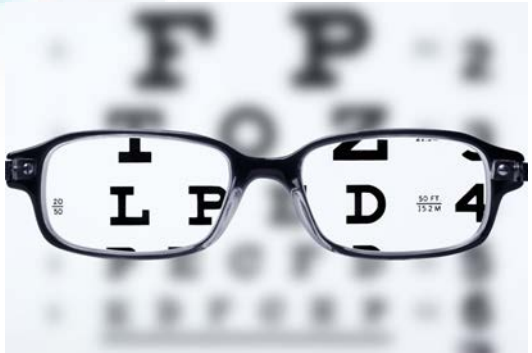


Wavefront : At λ Metrology

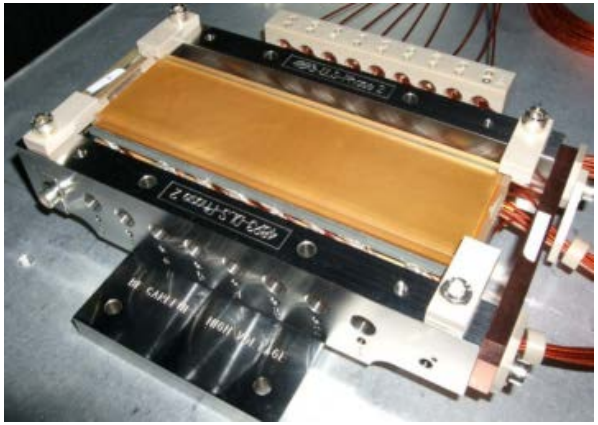


Surgery

Lenses or Glasses

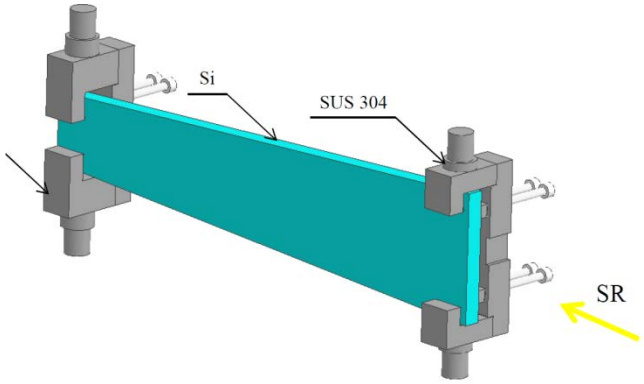


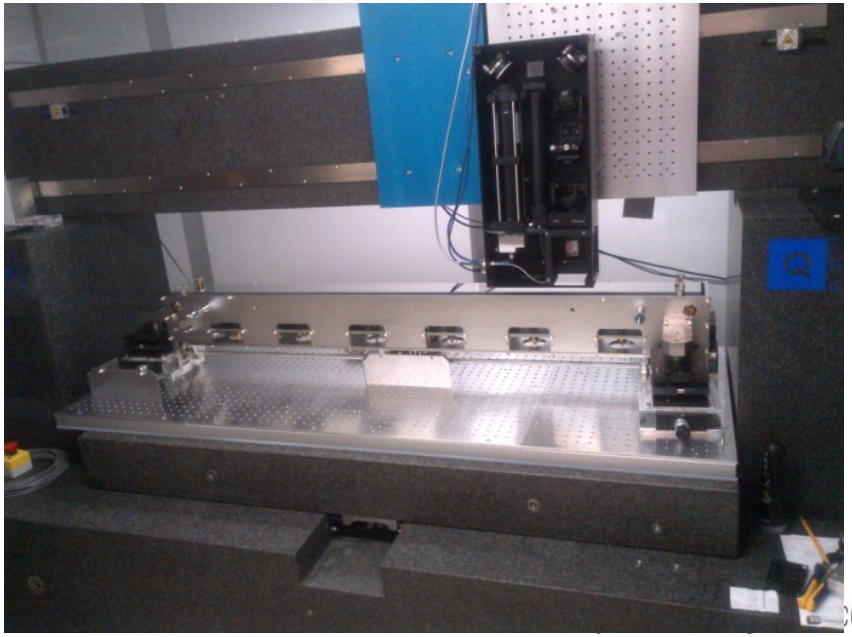
NSLSII X-ray Active Mirrors



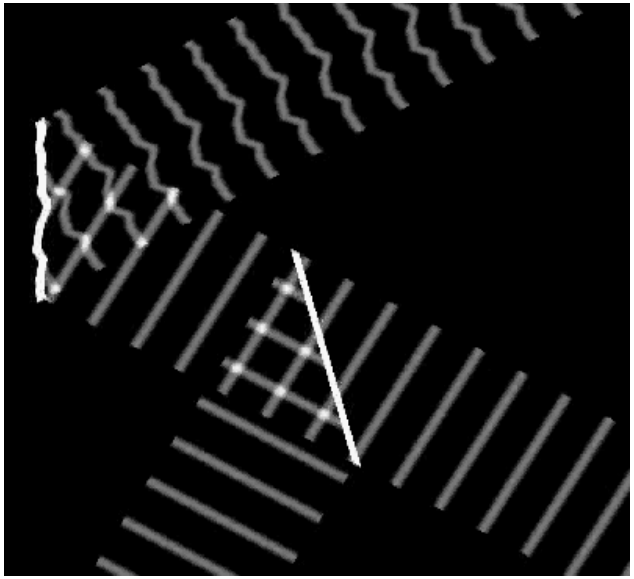
At least One active mirrors per beamline @ NSLS II (1 to 16 DoF per mirrors)

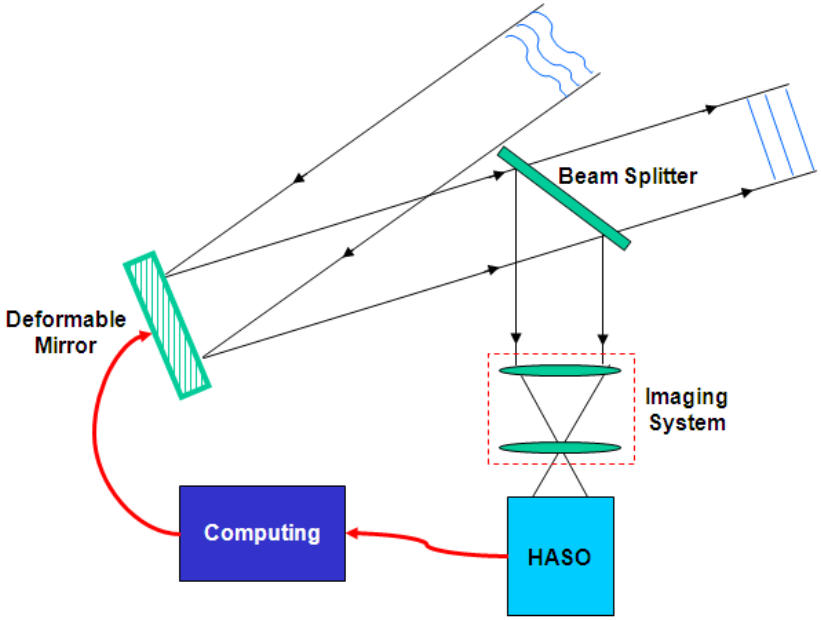
NEXT and ABBIX ~ 7 bimorphes mirrors





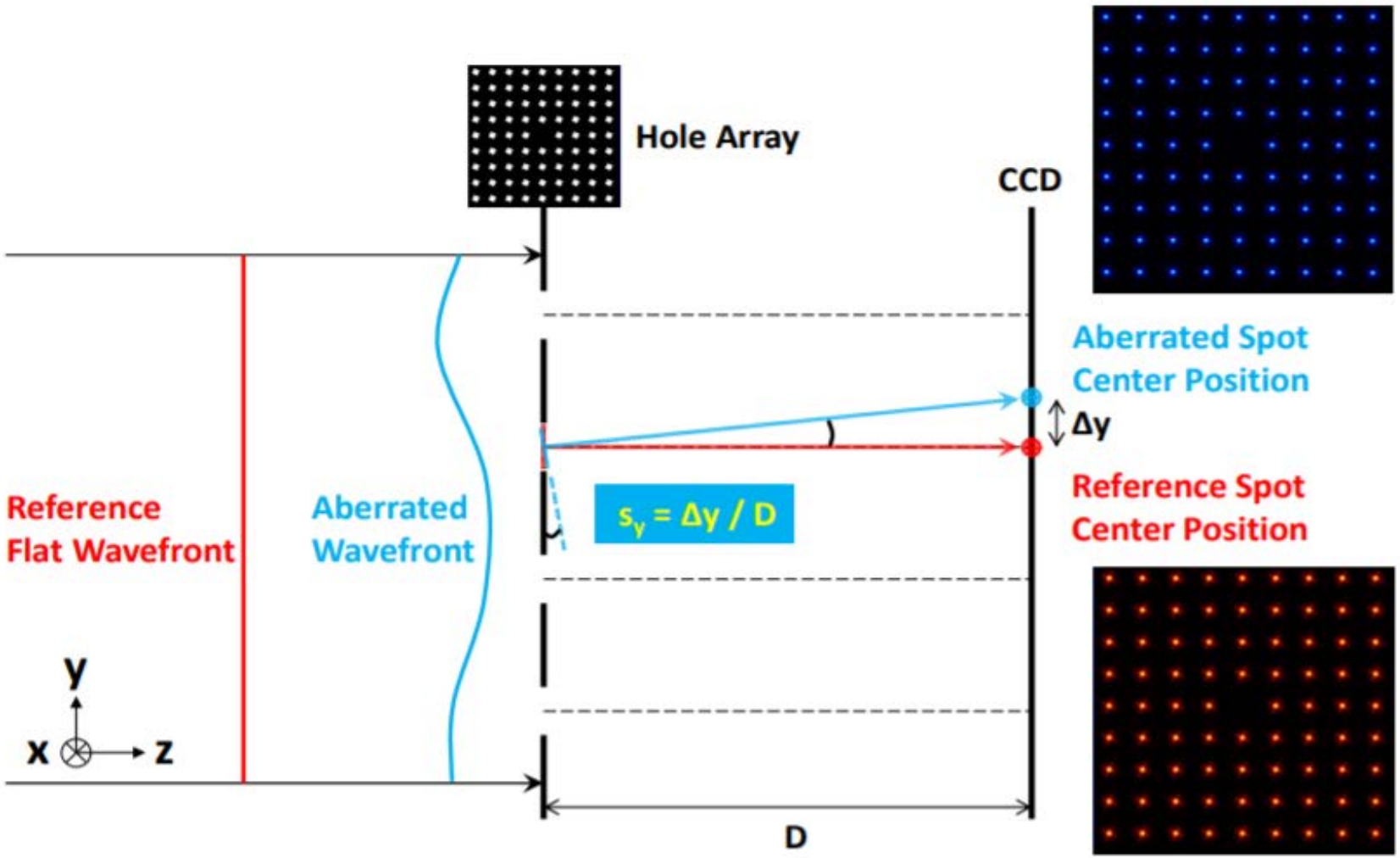
Adaptive Optics





A wavefront sensor
A wavefront corrector (deformable mirror)
A calculator

Hartmann Wavefront Sensor



Wavefront Preserving Mirrors project

Argonne National Laboratory

Lahsen Assoufid, (Co-Investigator and POC for ANL), Walan Grizolli, Xianbo Shi.

Brookhaven National Laboratory

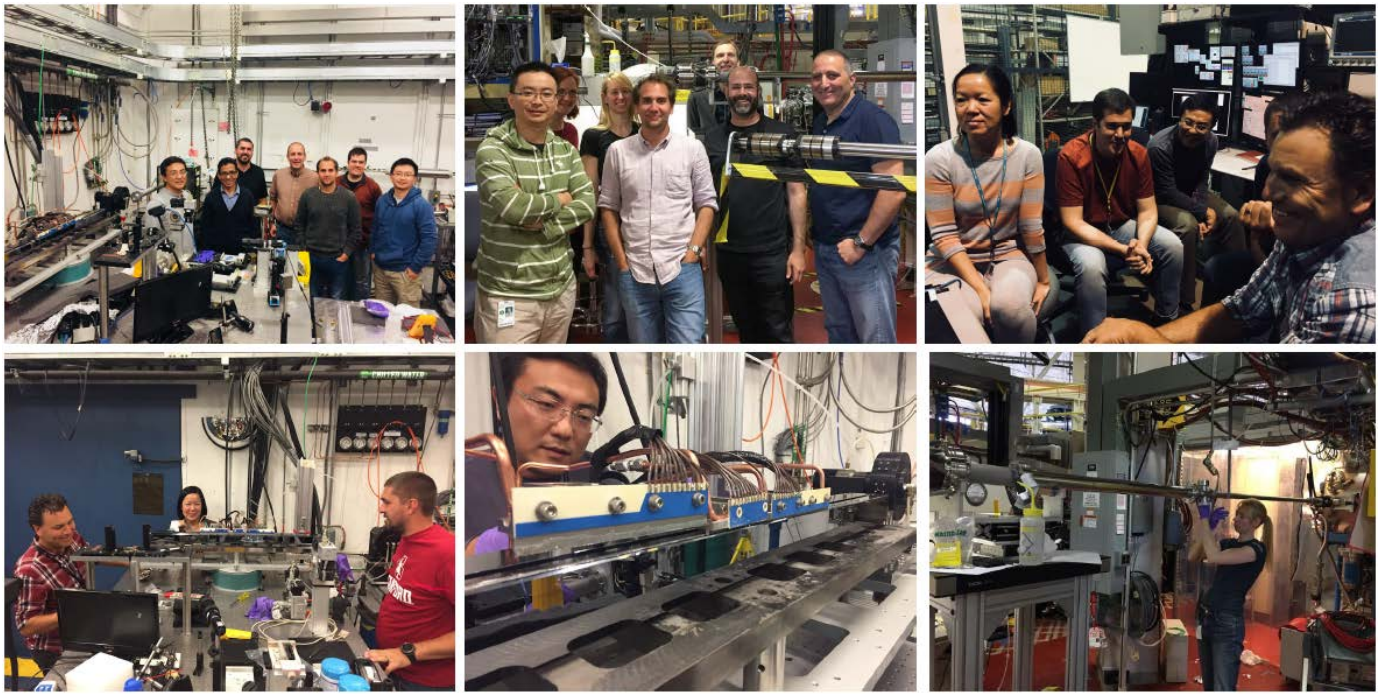
Mourad Idir, (Co-Investigator and POC for BNL), Lei Huang.

Lawrence Berkeley National Laboratory

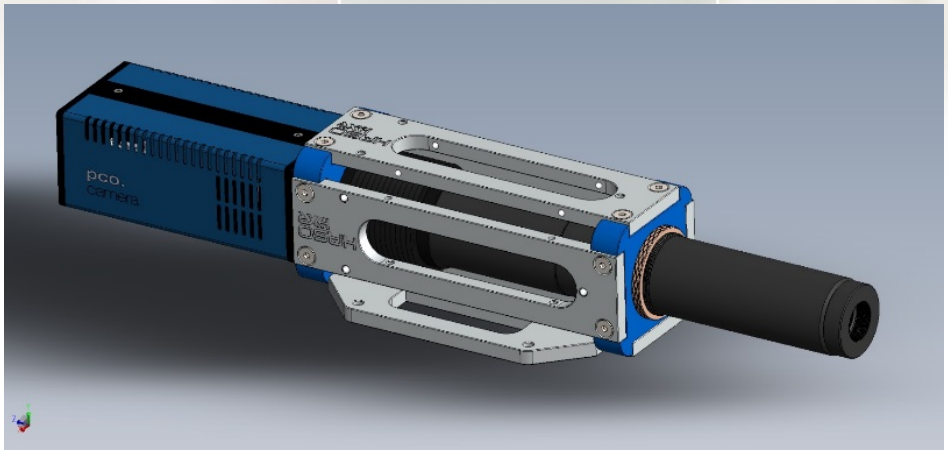
Kenneth Goldberg, (Co-Investigator and POC for LBNL), Diane Bryant, Antoine Wojdyla.

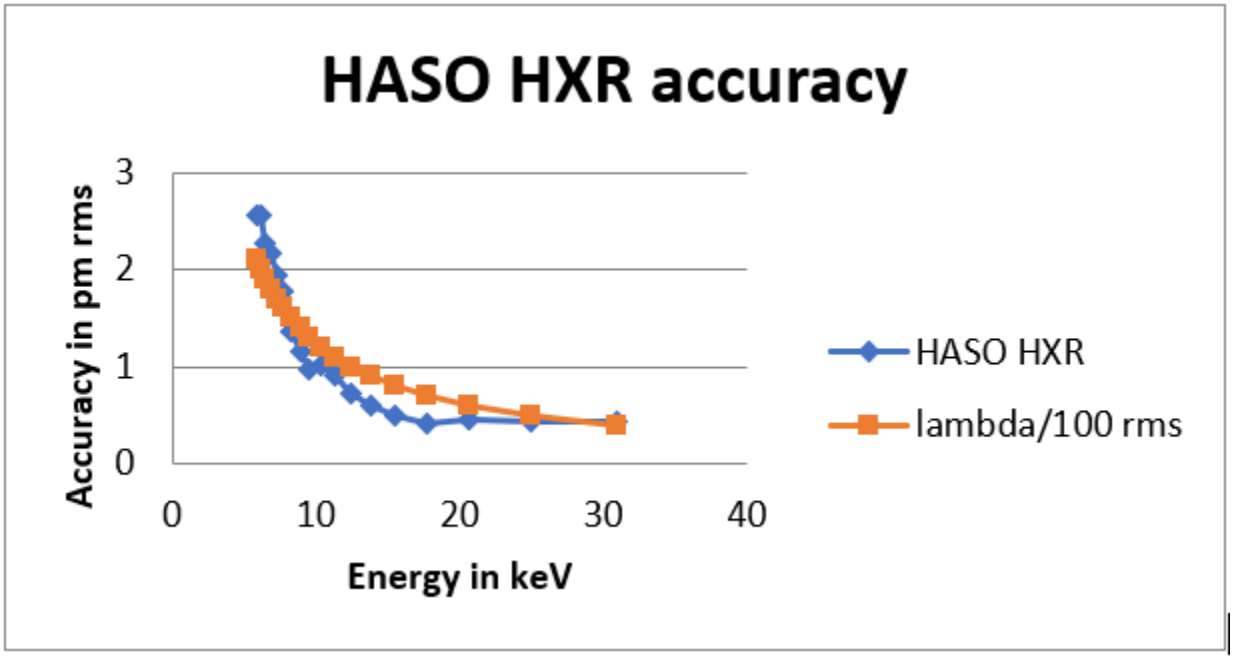
SLAC National Accelerator Laboratory

Daniele Cocco, (Principal Investigator and POC for SLAC), Corey Hardin, Daniel Morton, May Ling Ng.



Hartmann Wavefront Sensor



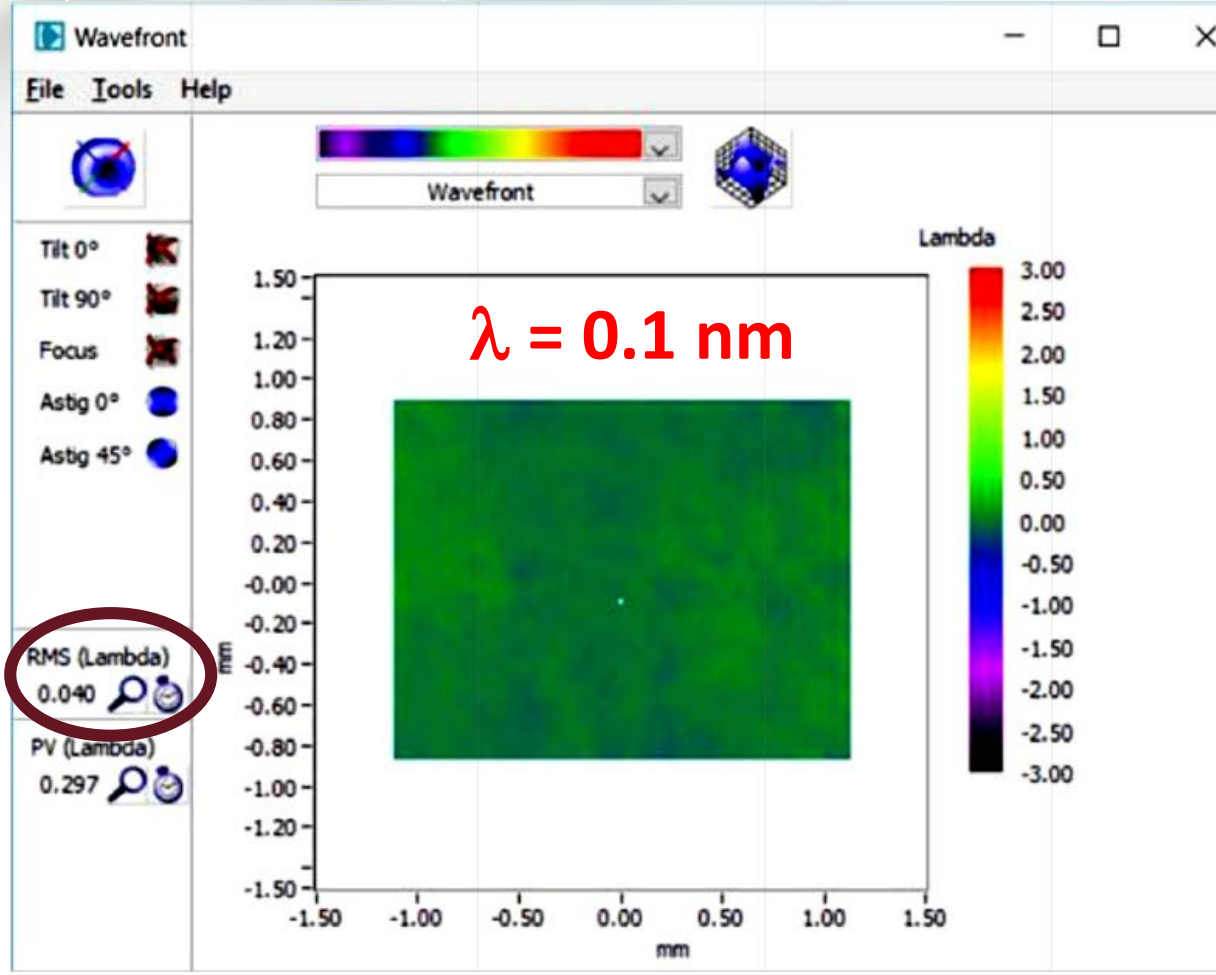


Sensitivity : 1pm rms
Accuracy : 2.5pm rms

Hartmann Wavefront Sensor

At λ/25 rms

The wavefront is much better than the limit of λ/14 given by Maréchal criterion and would produce a focal spot with a Strehl ratio as high as 0.82.

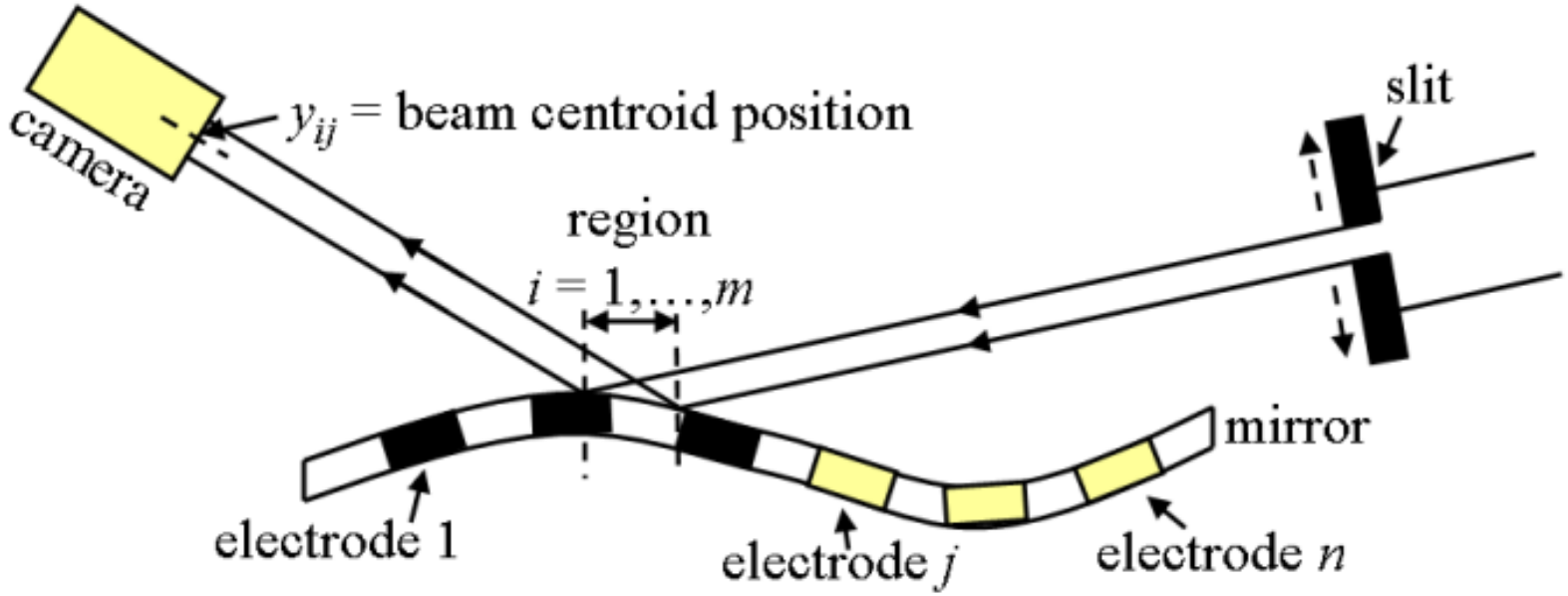


Reproducibility ~ λ/25 rms

Pencil Beam or Sequential Hartmann

Pencil-beam method: application to synchrotron beamlines

O. Hignette, A. Freund & E. Chinchio, *SPIE Proc.* **3152**, 188-199 (1997)

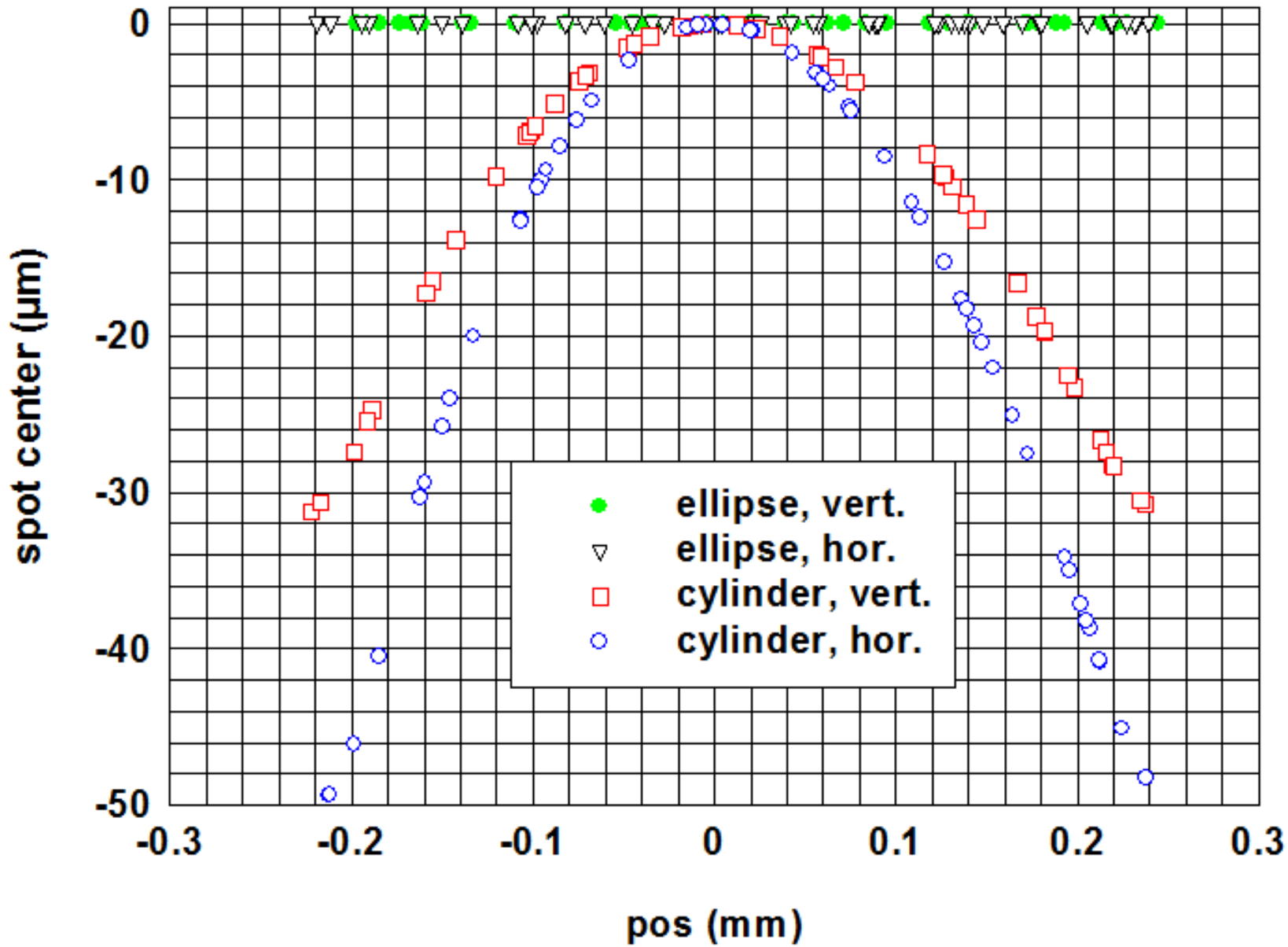


Upstream slit reduced to 10-20 μm

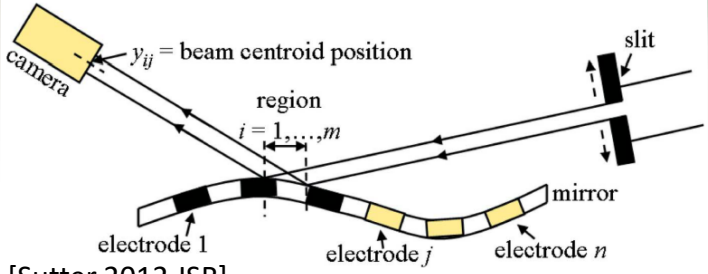
→ only small area (several mm) of mirror are illuminated at a time

Camera measures reflected beam position y_{ij} from ith section in jth scan.

No less than 2-3 points scanned per electrode.

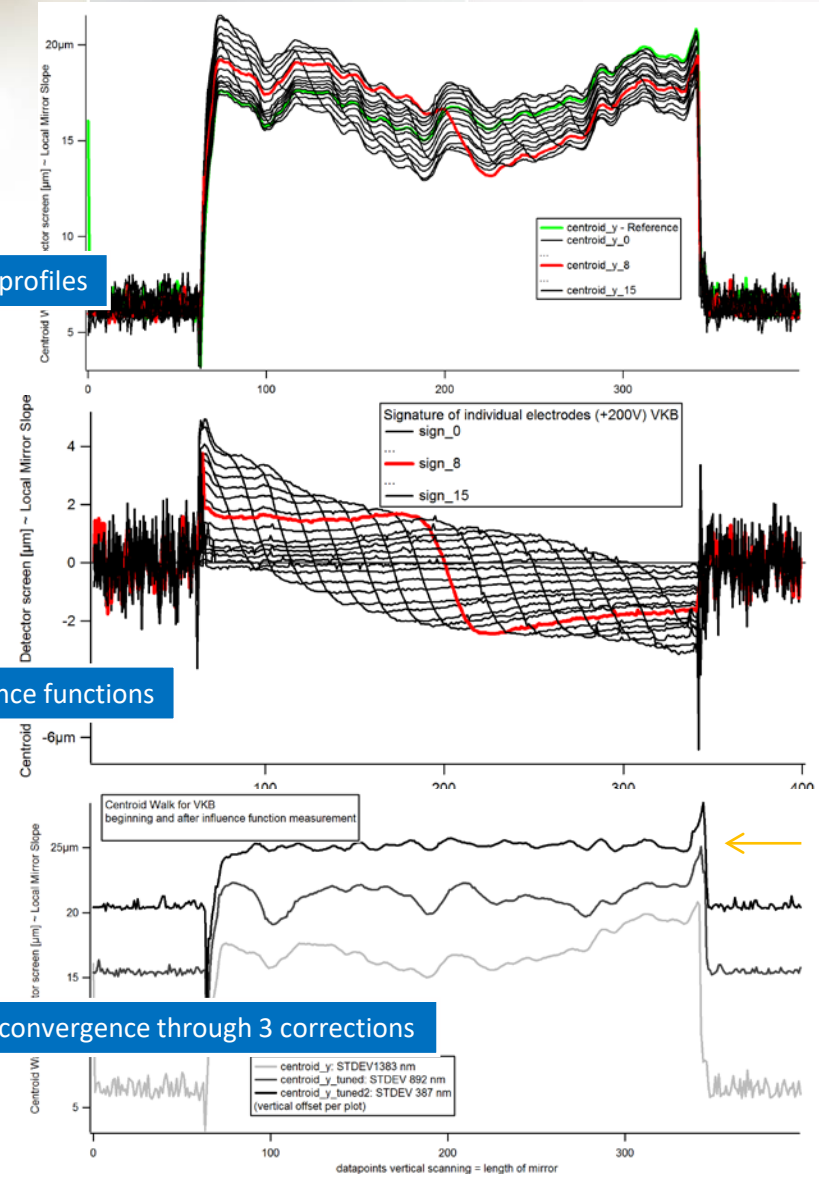

0
-10
-20
-30
-40
-50
spot center (μm)
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
pos (mm)
ellipse, vert.
ellipse, hor.
cylinder, vert.
cylinder, hor.

FMX Mirror commissioning: In-situ metrology



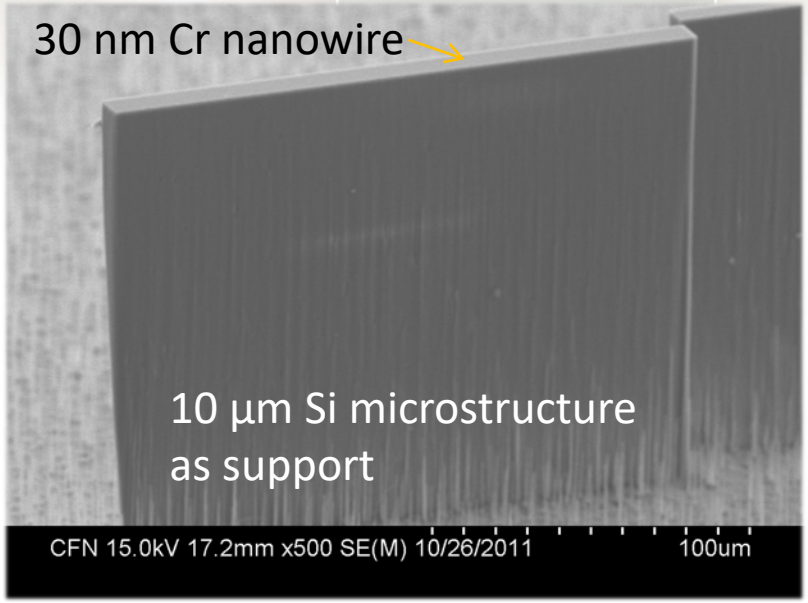
[Sutter 2012 JSR]

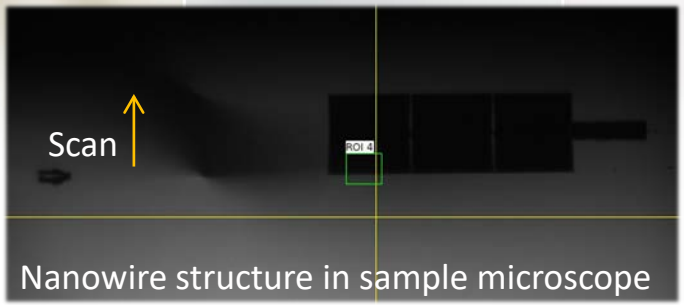
- 16-actuator bimorph piezo bender (SESO)
- Pencil beam scanning for in-situ slope measurement
- Fast fly scan implementation: 1-2 min / scan
  - ➢ Influence functions for each electrode
  - ➢ Convergence after 3 iterations
  - ➢ Recover LTP metrology results
- Top hat beams next

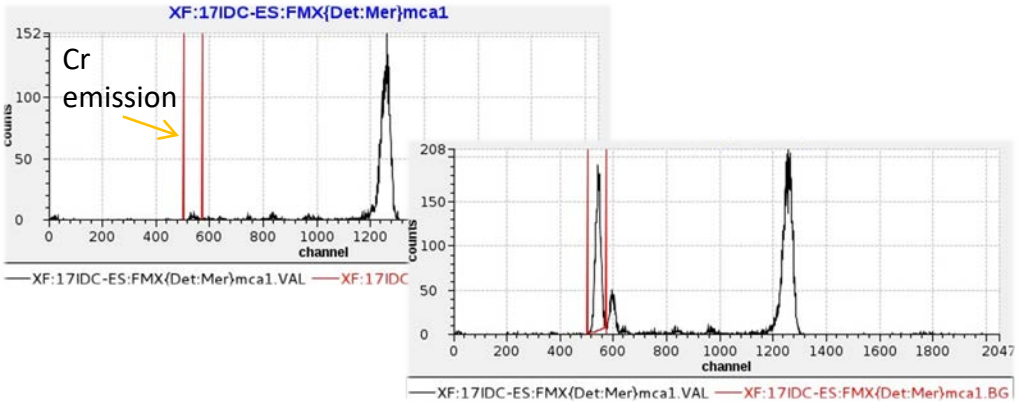


Huang, L.; Xue, J. & Idir, M. "Controlling X-ray deformable mirrors during inspection" *J. Synchrotron Rad.*, **2016**, *23*, 1348-1356

FMX beam size measurements

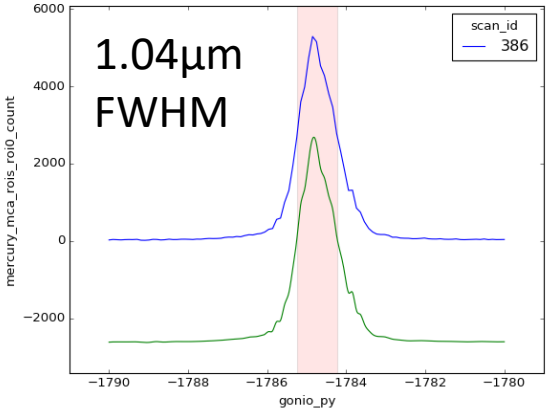




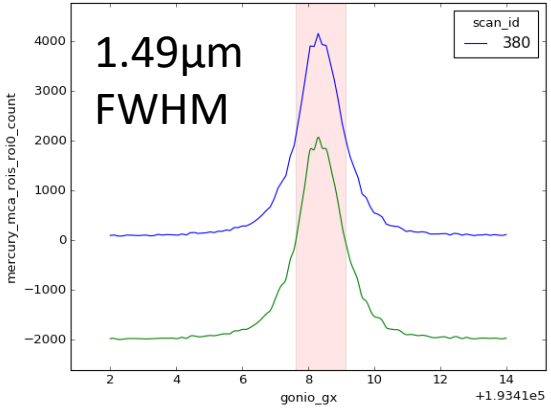


- Beam size by Cr nano-wire scan with fluorescence detection
- Bluesky scan of Cr fluorescence ROI counts

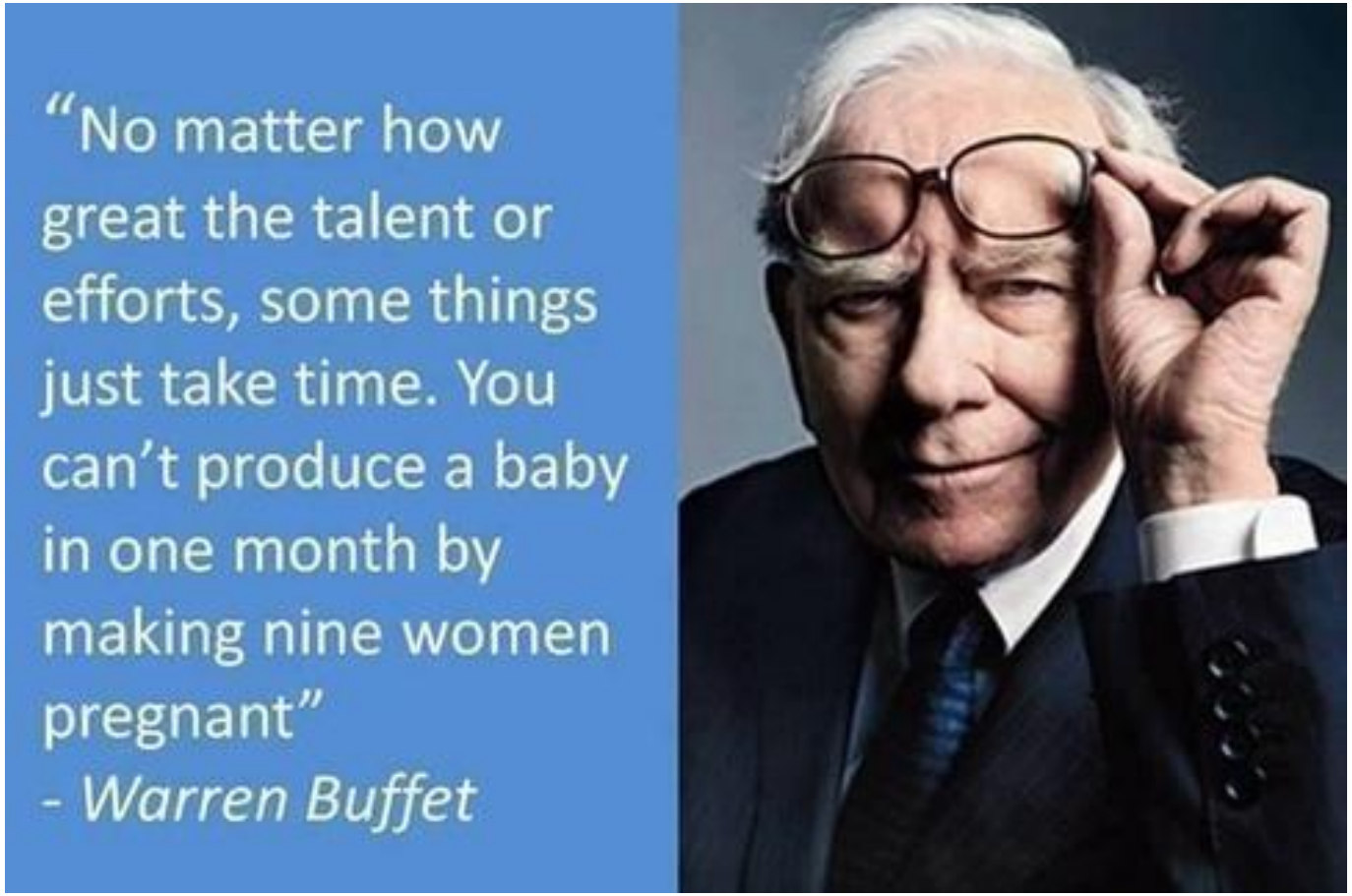
Vertical focus



Horizontal focus



Thank you for your attention



BACKUP SLIDE

Progress Report of One-Dimensional IBF on Sphere and Flat Mirrors

02/06/2019

U.S. DEPARTMENT OF ENERGY | Office of Science
BROOKHAVEN NATIONAL LABORATORY

Experimental Specification 1

Rectangular Sphere (RS) Mirror (Length = 100mm)				
Measured Length (mm)	Clear Aperture (mm)		Target Radius (m)	Roughness After IBF (nm)
98	1st to 3rd runs 2 ~ 96	4th and 5th runs 2 ~ 93	30.29	0.34

Circular Flat (CF) Mirror (Diameter = 100mm)		
Measured Length (mm)	Clear Aperture (mm)	Roughness After IBF (nm)
101	2 ~ 90	To Be Added

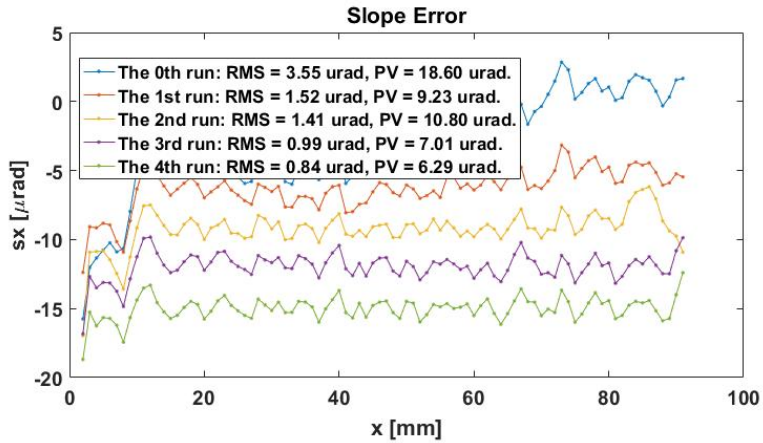
Experimental Specification 2

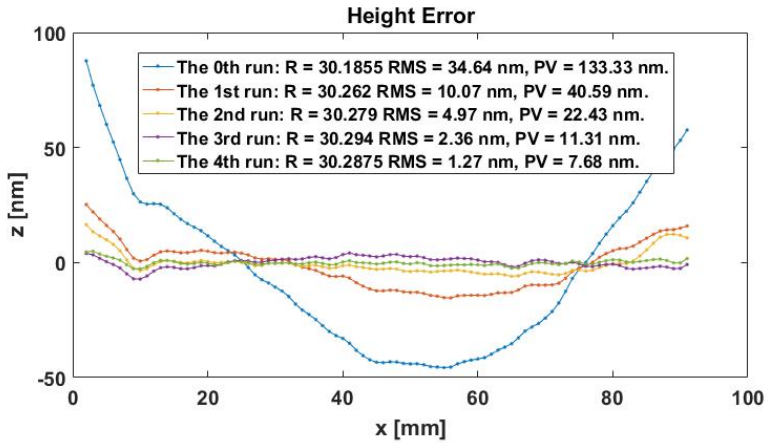
Substrates used for the mirrors.

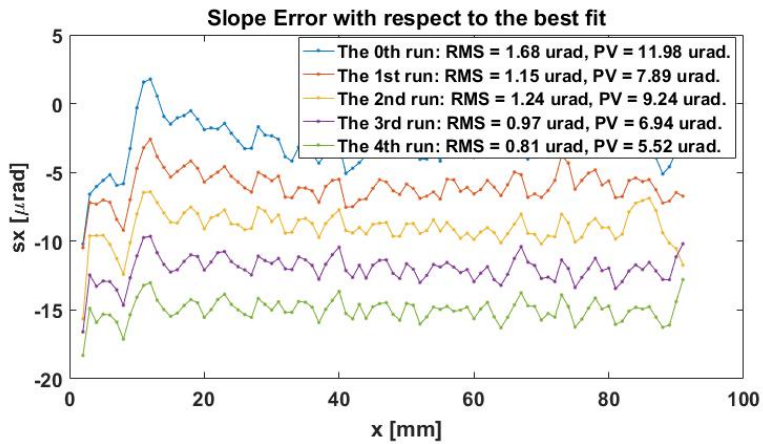
Methods

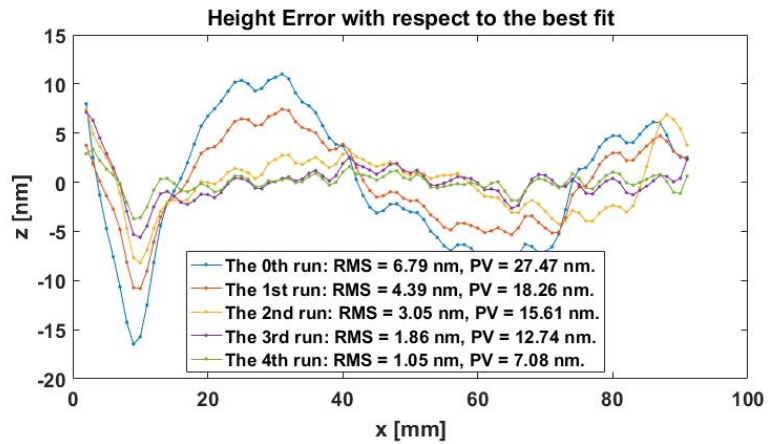
- Put both the reference mirror and the IBF mirror in the same substrate to facilitate both the beam removal function estimation (BRF) and the calibration of different coordinate systems.
- Coarse-to-fine dwell-time optimization algorithm:
  - Coarse level: calculating dwell-time without constraints, followed by polynomial fitting the resulted dwell-time.
  - Fine level: obtaining the residual after the polynomial fitting, followed by calculating the dwell-time for the residual with constraints on the maximum time difference between each two consecutive dwelling positions.
  - Add the resulted dwell-times of both the coarse and fine level results.
- Adding a scaling factor to the final dwell-time to solve the overshooting problem of the BRF

Results - IBF on RS Mirror 1 (1 ~ 90mm)

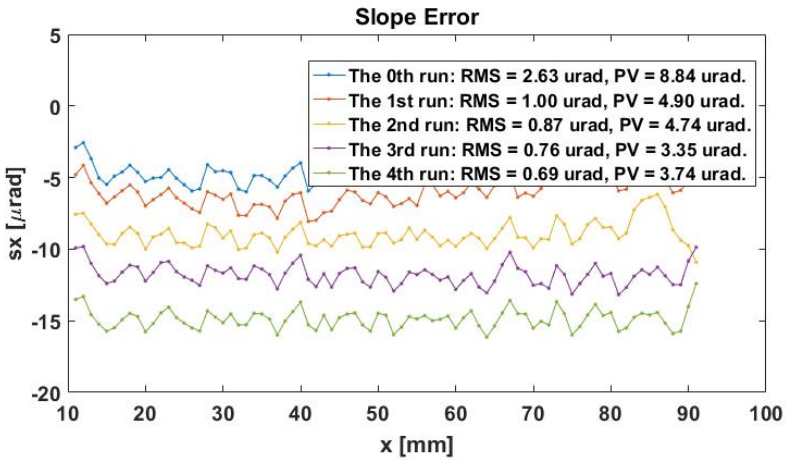


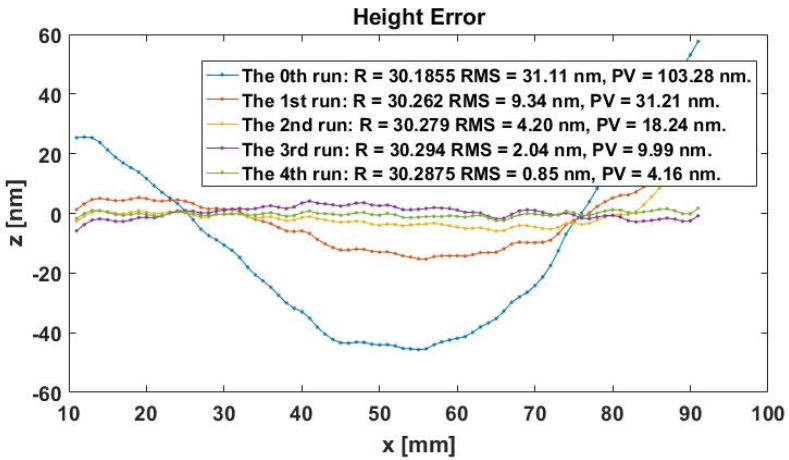


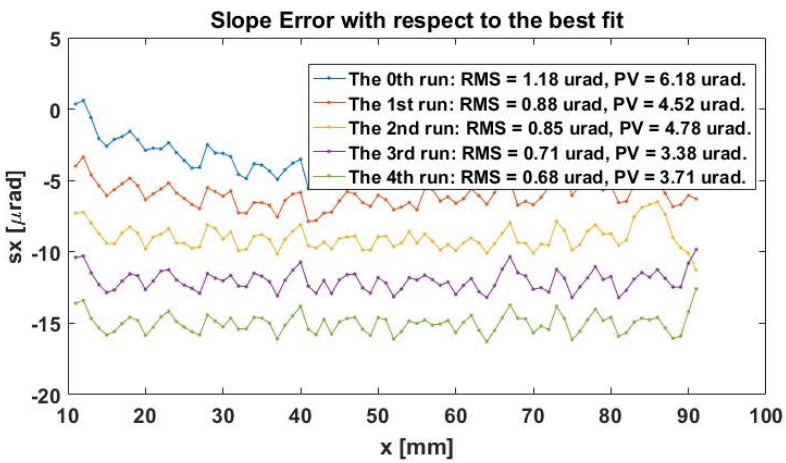


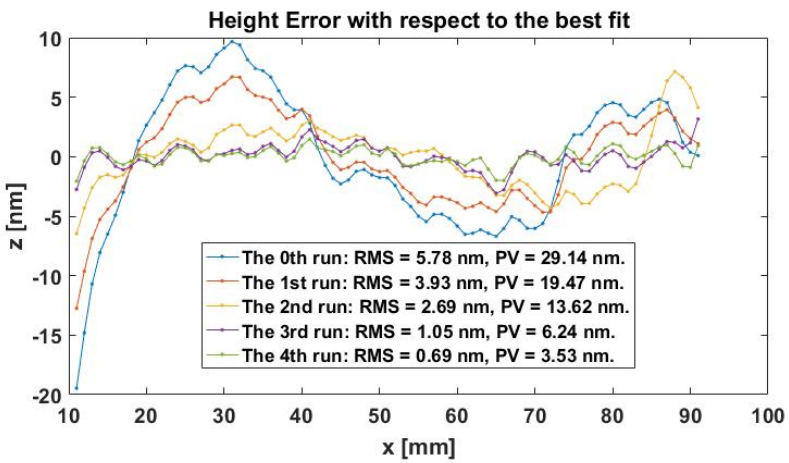


Results - IBF on RS Mirror 2 (10 ~ 90mm)





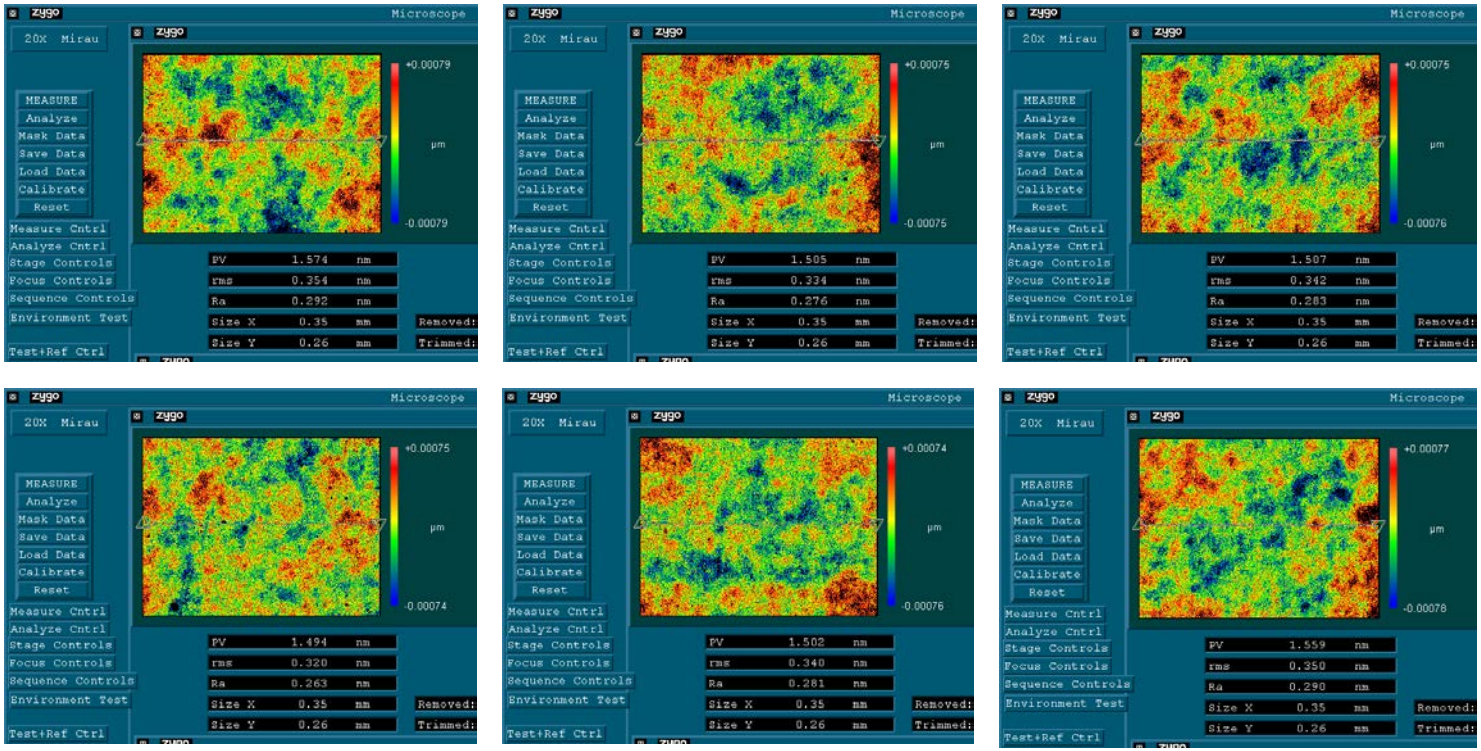
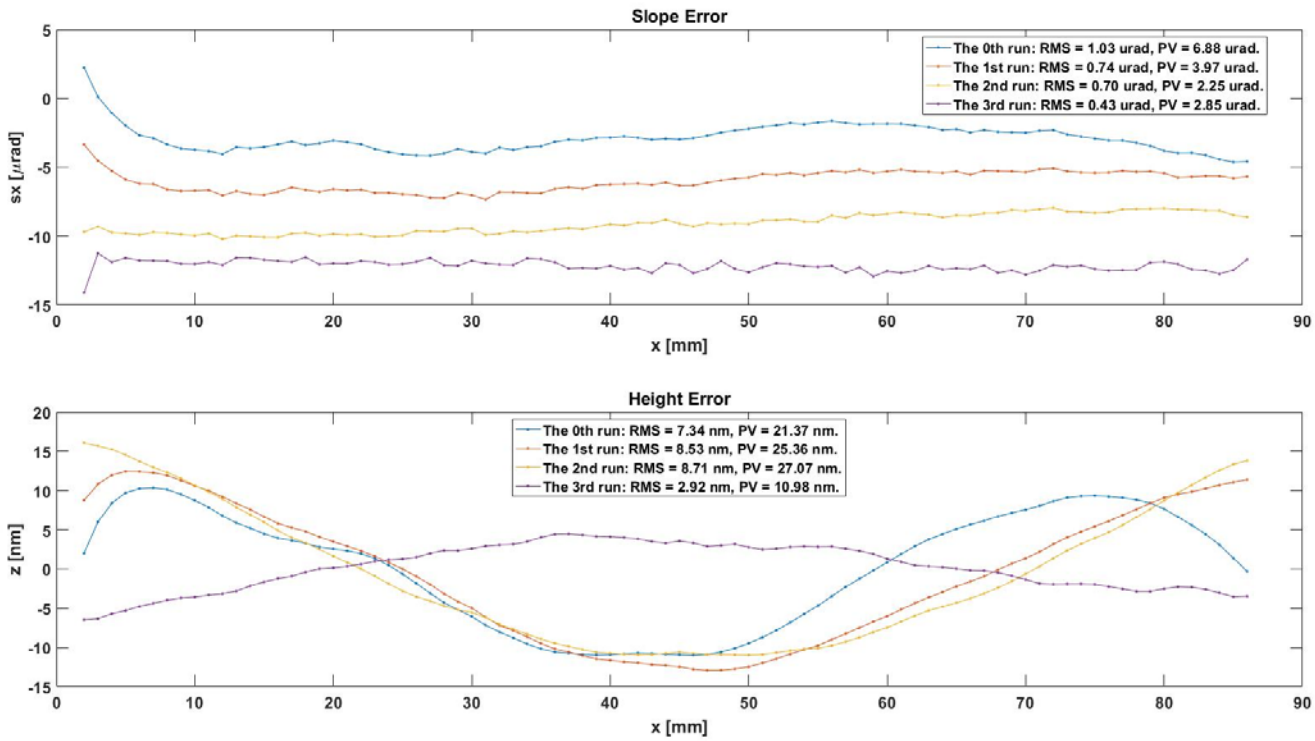




Results - IBF on RS Mirror - Micro Roughness

Before IBF

After IBF



Results - IBF on CF Mirror 1 (10 ~ 90mm)