National Synchrotron Light Source II

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Diffraction-limited reflective optics development at NSLS-II

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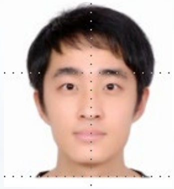
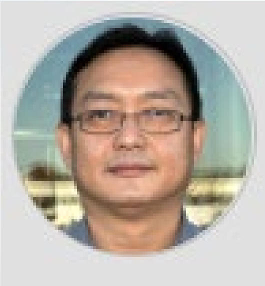


Tianyi Wang
coPI

Support from
Nathalie Bouet
Thin Film

Yi Zhu
Engineering

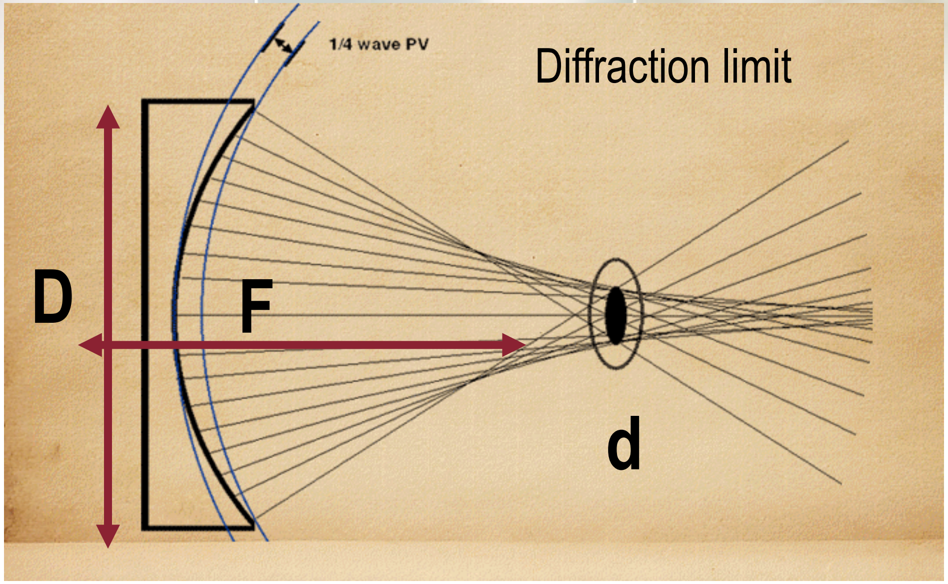


OUTLINE

Diffraction-limited reflective optics development at NSLS-II

- *NSLSII mirror metrology*
- Ion Beam Figuring @ NSLSII
  - *Principle – Capabilities*
  - *Examples*
- New R&D Direction

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



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

$$d \approx 20\ nm$$

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

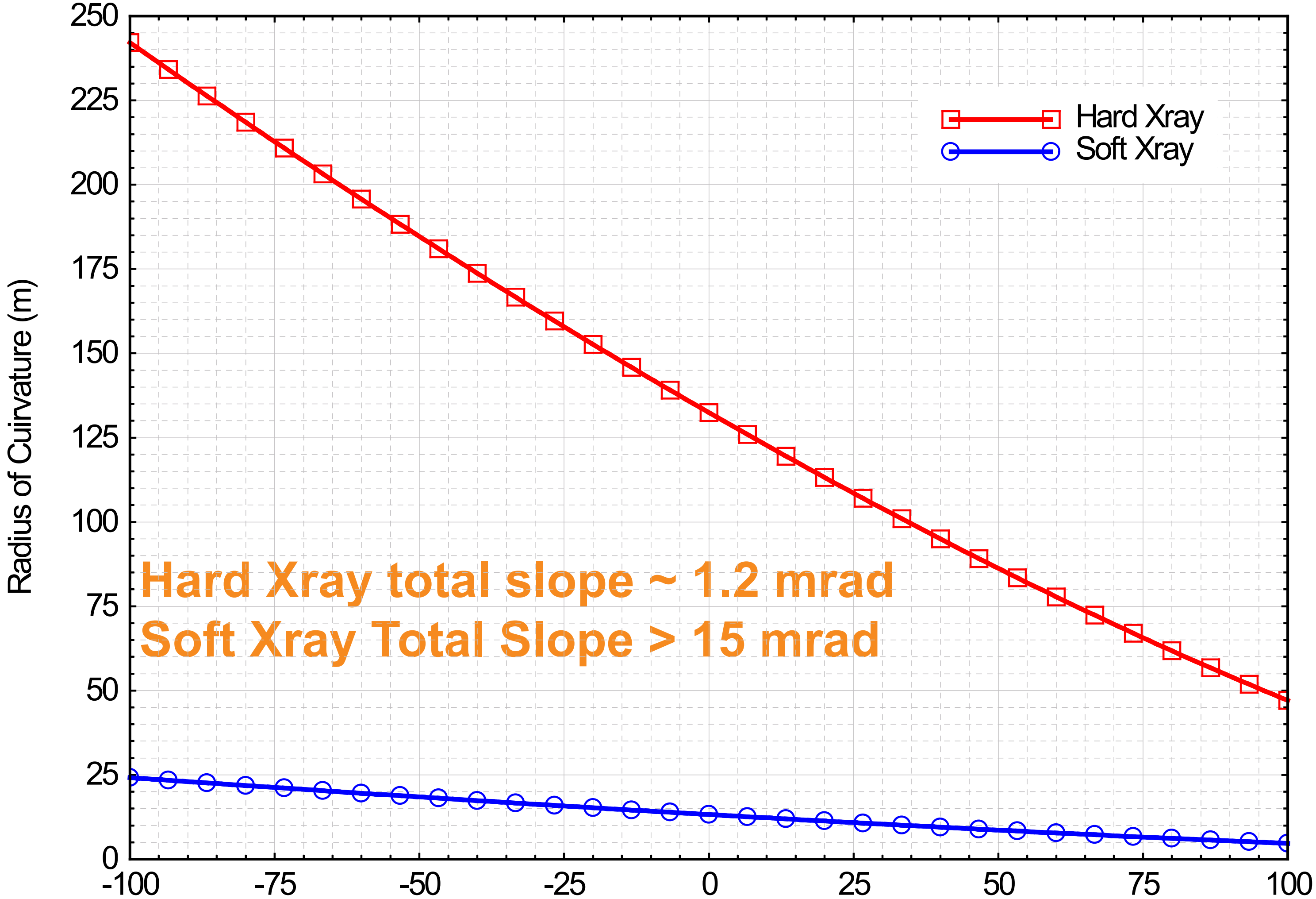
Soft x-ray: $\lambda = 1$ nm $\theta = 30$ mrad

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

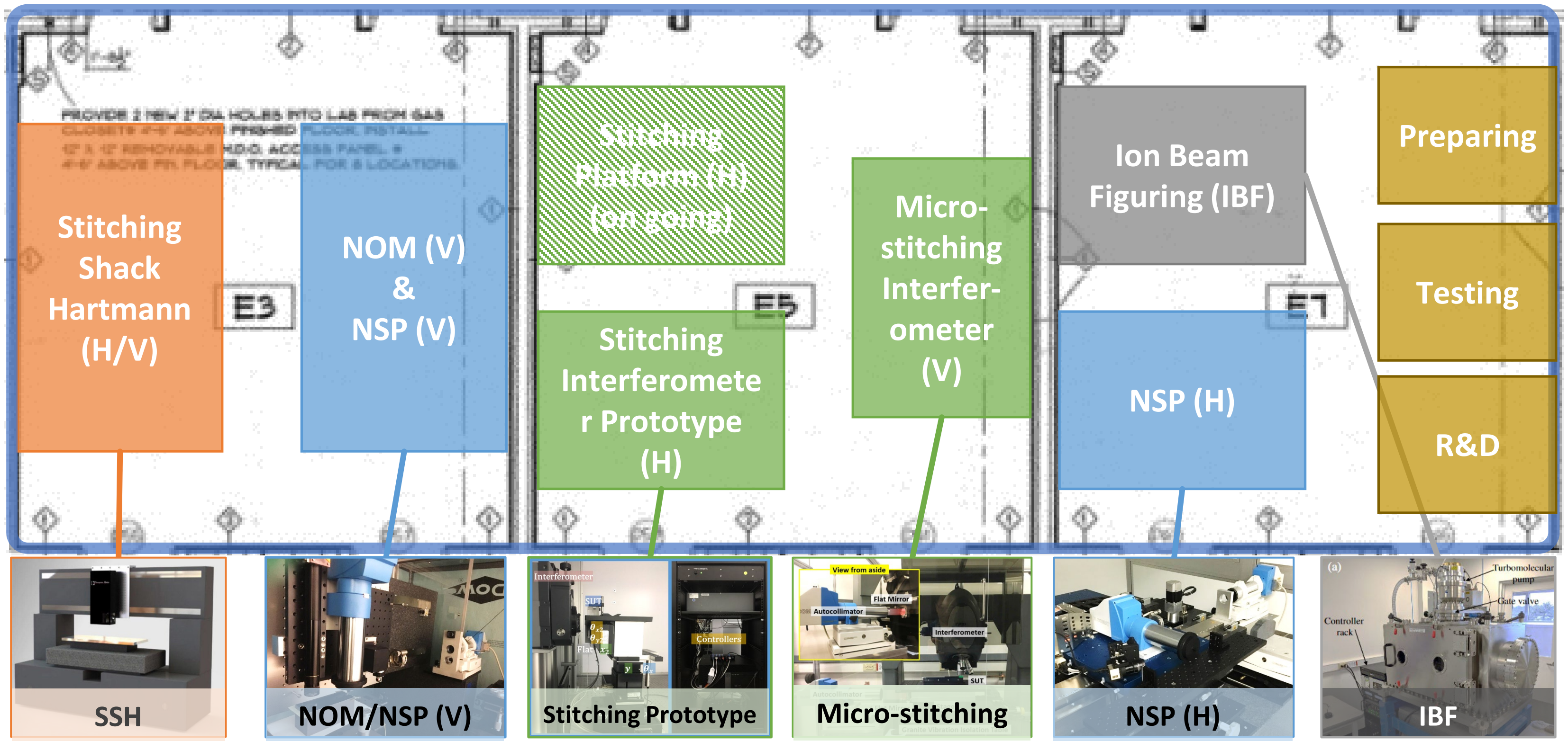
Slope < 100 nrad rms
Height < 1.1 nm rms

Mirror Shape error λ/280θ rms

Slope < 100 nrad rms Height < 1.1 nm rms

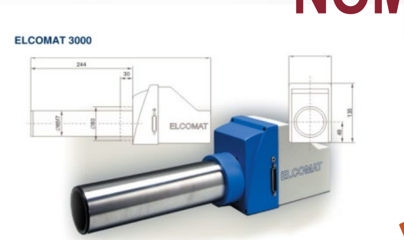


NSLSII Optics R&D and metrology lab

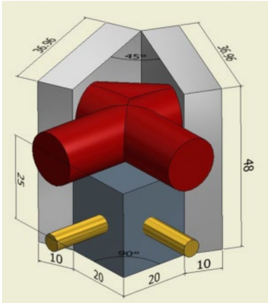


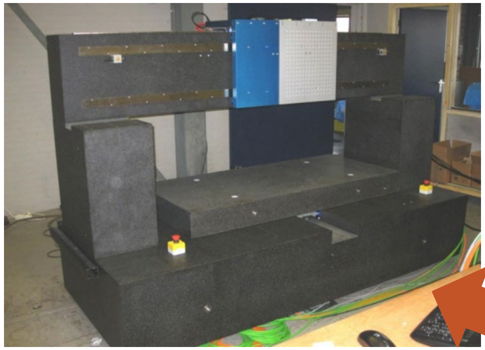
Slope measuring devices

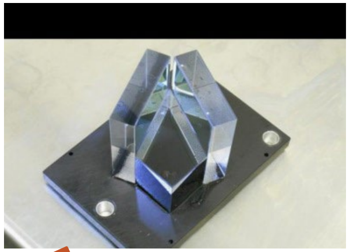
NOM



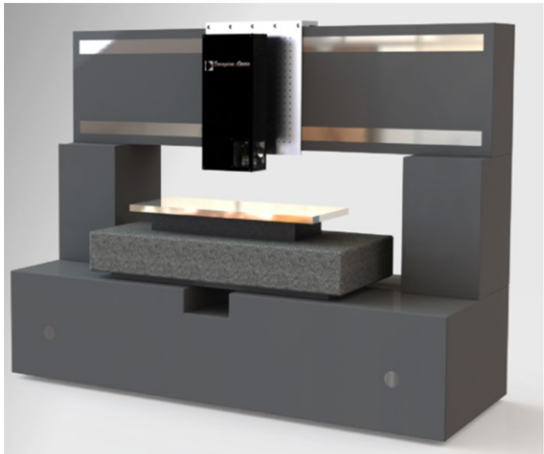
High accuracy Autocollimator





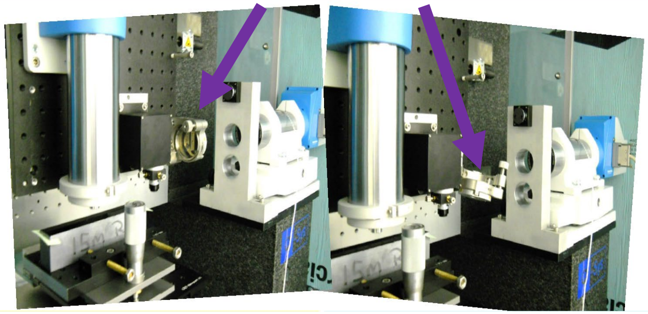


Stitching Shack Hartmann Optical Head : SSHOH



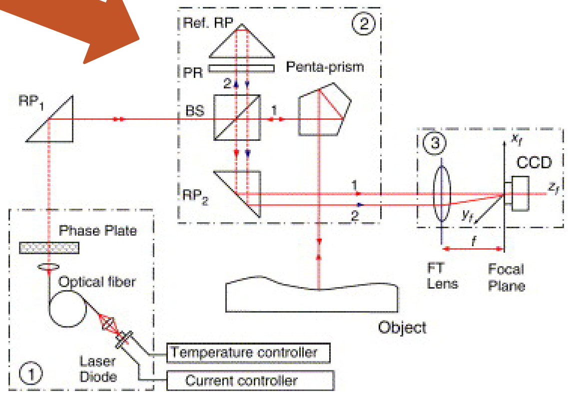
Nano Surface Profiler

Flipping Mirror NSP to NOM



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

LTP

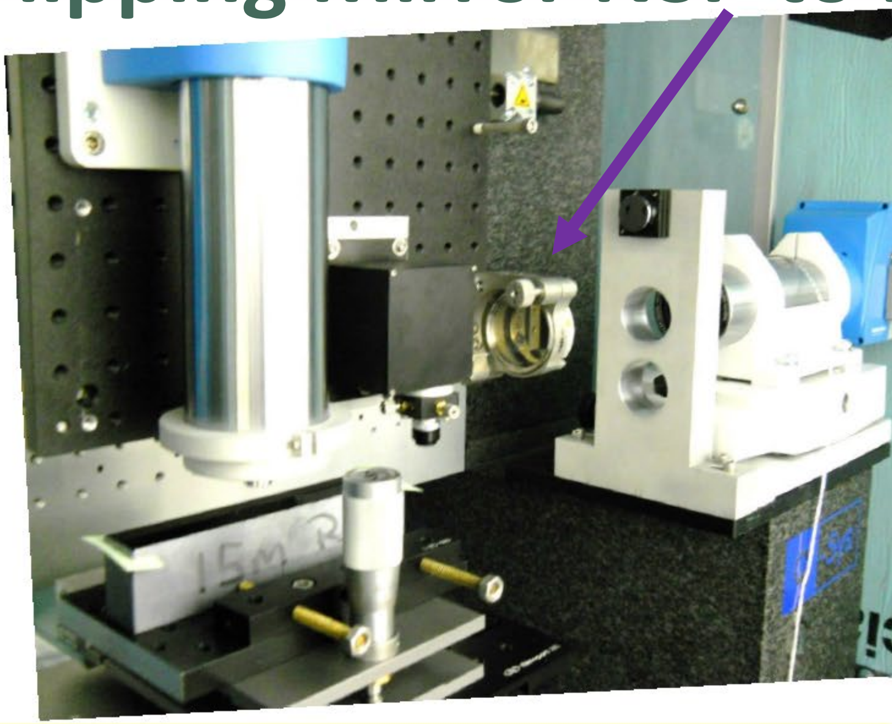


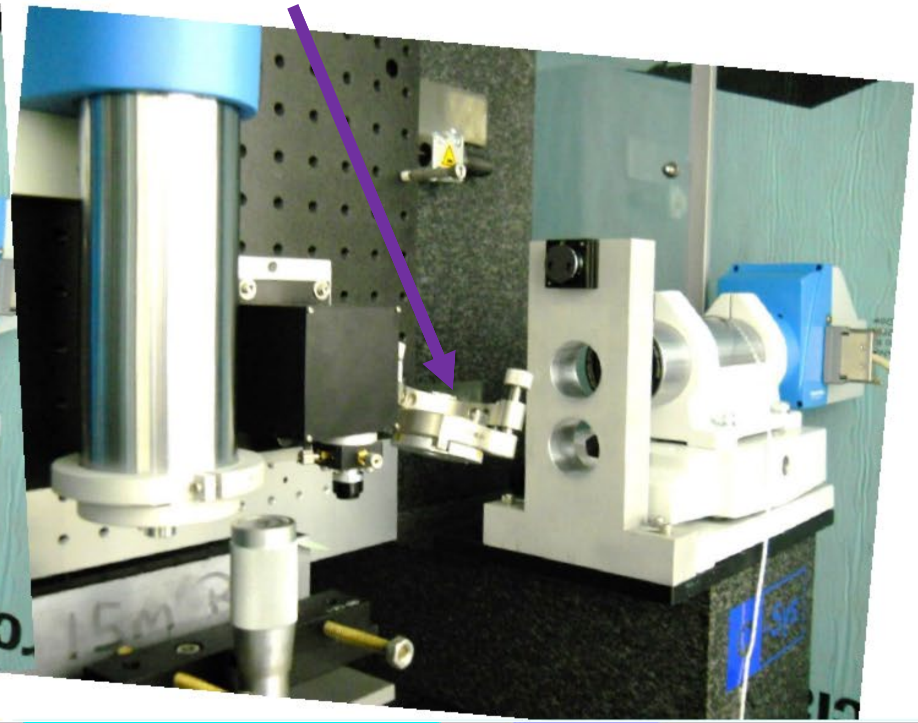
Deflectometry based Optical Metrology Station

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

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

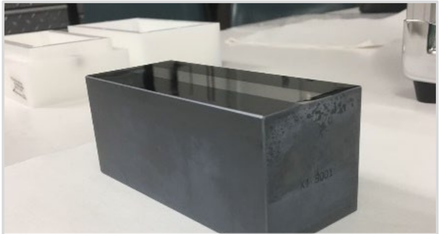
Flipping Mirror NSP to NOM



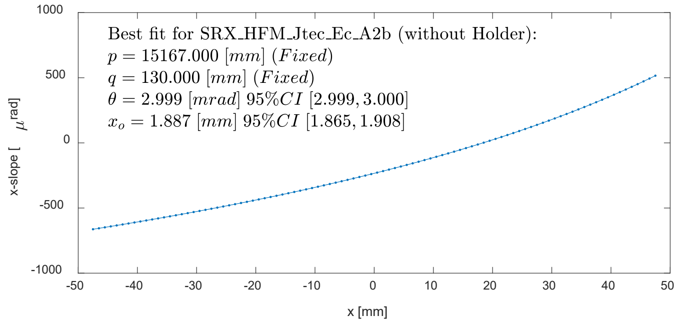


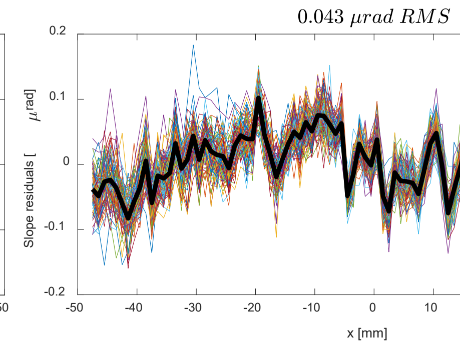
Easy switching between **NSP** and BNL-**NOM**

KB mirror inspection by using NSLS-II vertical NSP



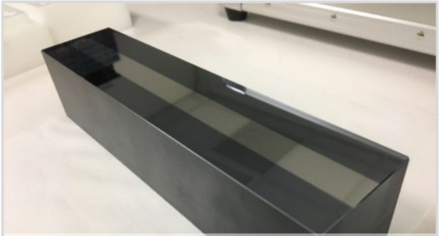
NSLS-II SRX
horizontal nano-KB



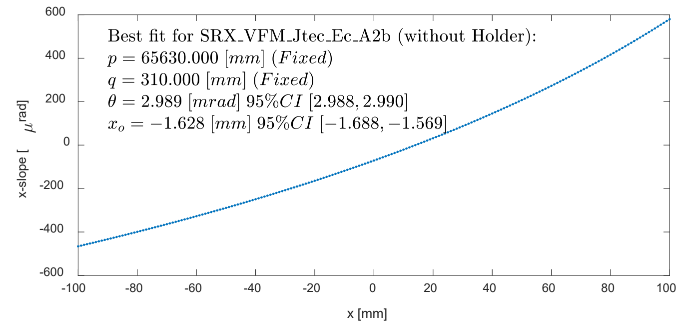


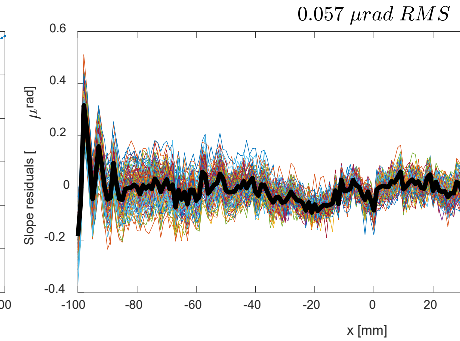
< 50 nrad RMS

Slopes **Slope errors**



NSLS-II SRX
vertical nano-KB





< 70 nrad RMS

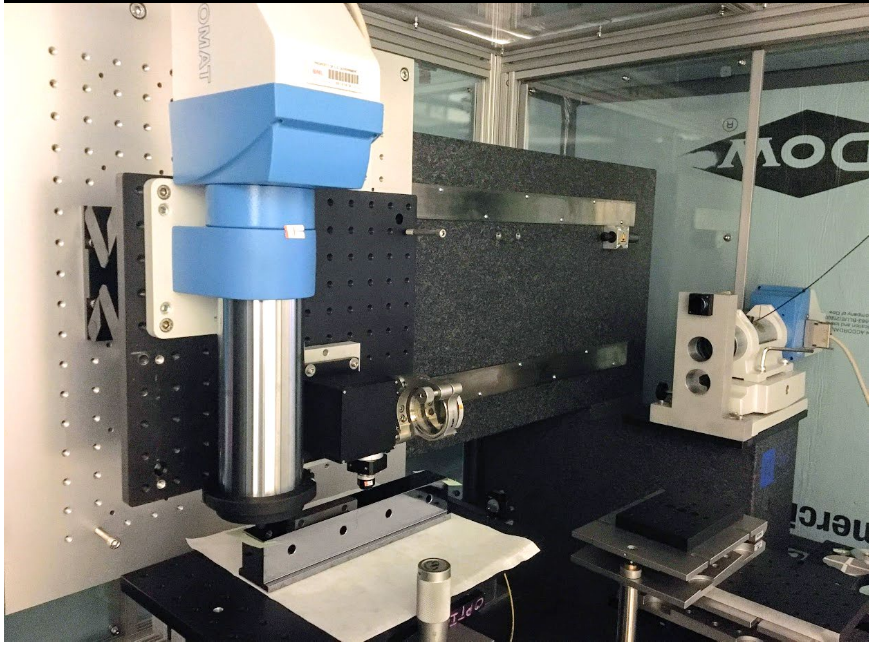
Excellent instrument but

- 1D
- Limited to 10 mrad Systematic errors

NSLS-II FIP (metrology upgrade)

Lei Huang (PI), Lukas Lienhard, Tianyi Wang, Steven Hulbert, and Mourad Idir

NSLS-II vertical NSP before upgrade



Challenges

Inspection of >10 mrad X-ray mirrors

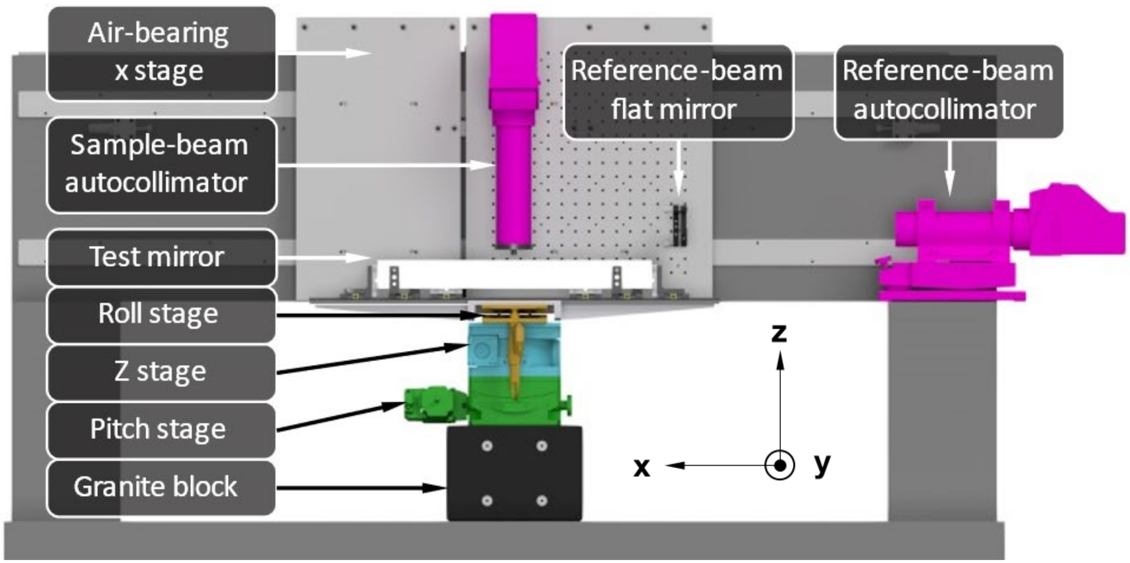
Before upgrade	Upgrade objective
10 mrad measuring range **with uncalibrated instrument errors**	>10 mrad measuring range **with self-calibration and stitching capability**

Our solution

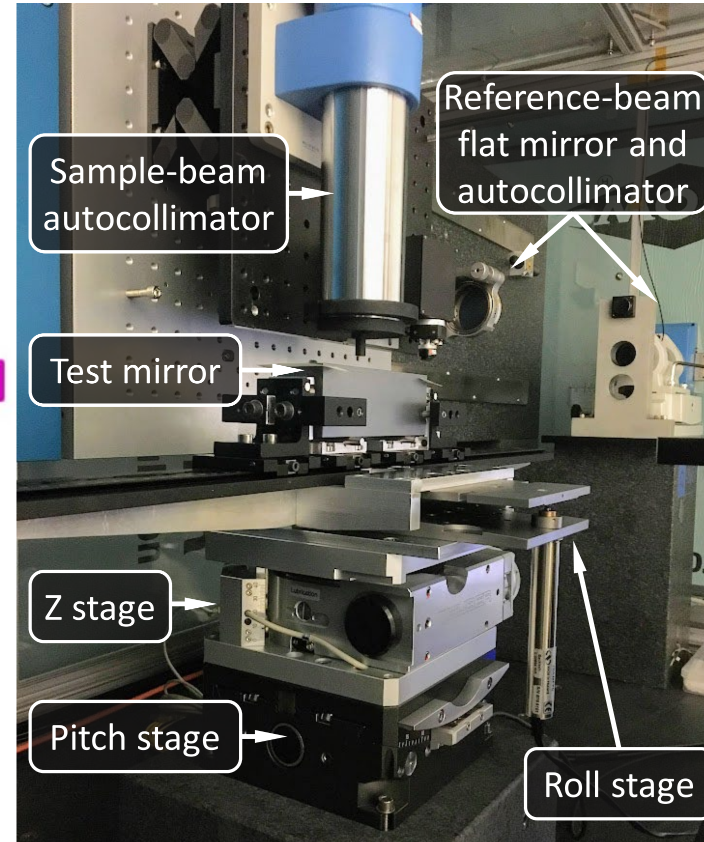
Multi-Pitch NSP (MPNSP) upgrade

Huang L, Wang T, Nicolas J, Polack F, Zuo C, Nakhoda K, et al. Multi-pitch self-calibration measurement using a nano-accuracy surface profiler for X-ray mirror metrology. Opt Express (2020)

Multi-pitch NSP (MPNSP)



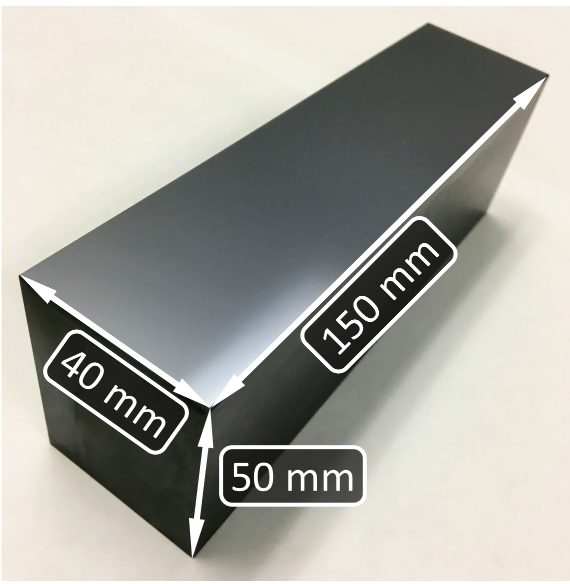
Mechanical design by Lukas Lienhard



Photograph of the actual setup

1. F. Polack, M. Thomasset, S. Brochet, and A. Rommeveaux, Nucl. Instrum. Methods Phys. Res., Sect. A (2010)
2. L. Huang, T. Wang, J. Nicolas, F. Polack, et al. Opt Express (2020)
3. L. Huang, T. Wang, F. Polack, et al. Frontiers in Physics (2022)

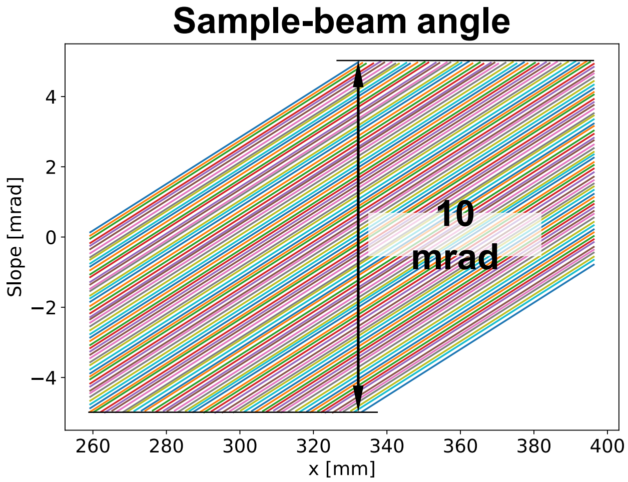
Test example by using the MPNSP technique

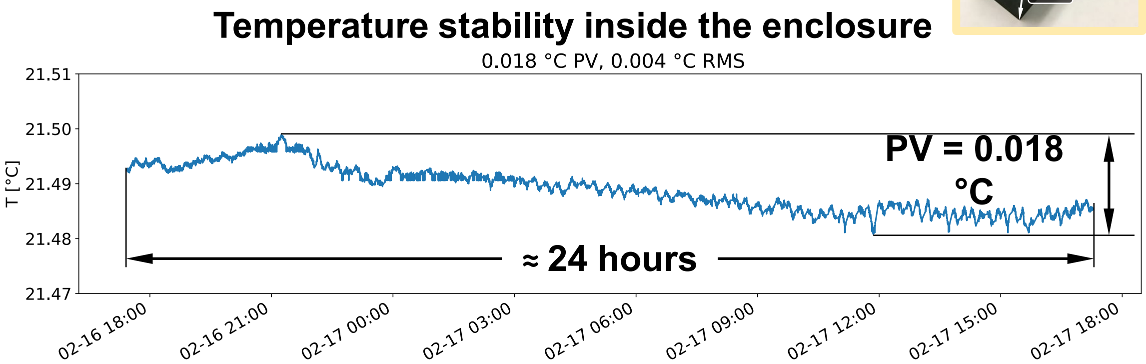


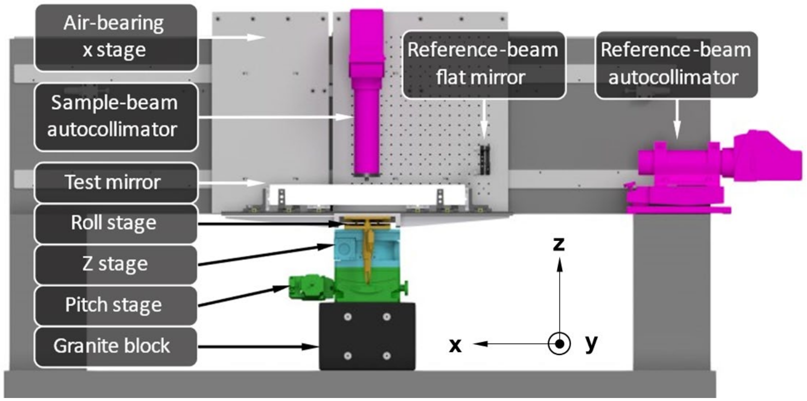
- Si mirror fabricated by JTEC Corp
- Circular cylinder, RoC ≈ **15 m**
- The length of optical area is **141 mm**
- Total slope range is around **10 mrad**

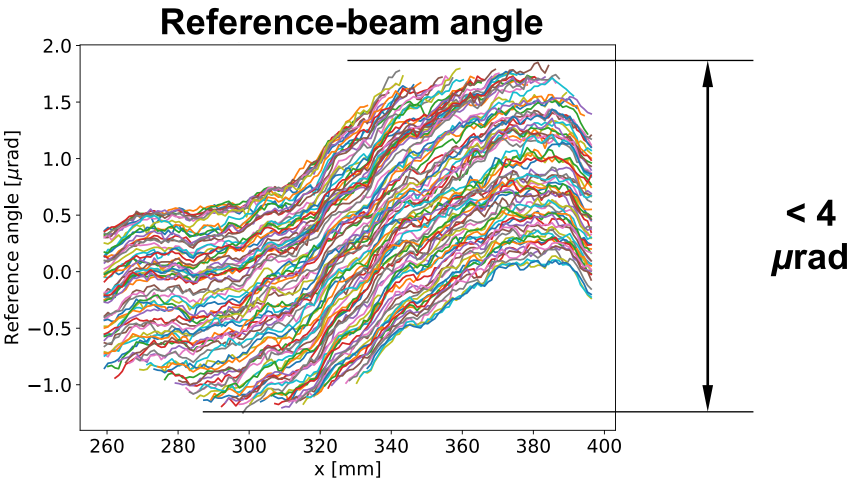
This mirror are measured with **MPNSP** in both **A-to-B** and **B-to-A** orientations

Data acquisition in the MPNSP







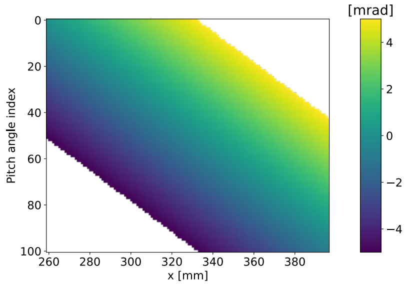


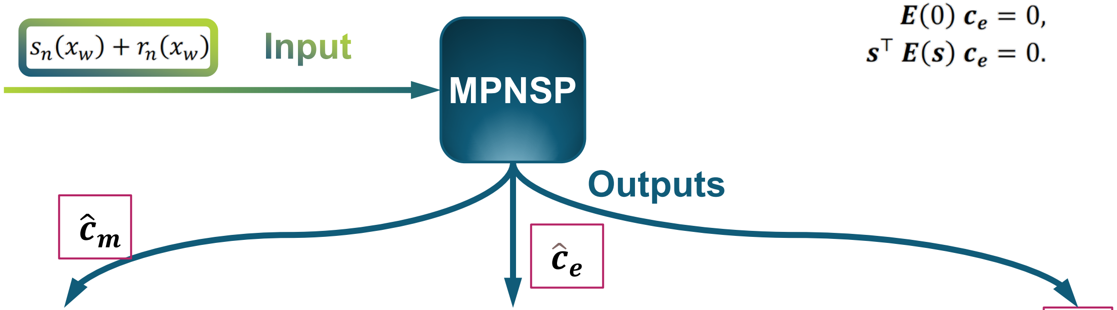
Multi-pitch Nano-accuracy Surface Profiler

MPNSP Results

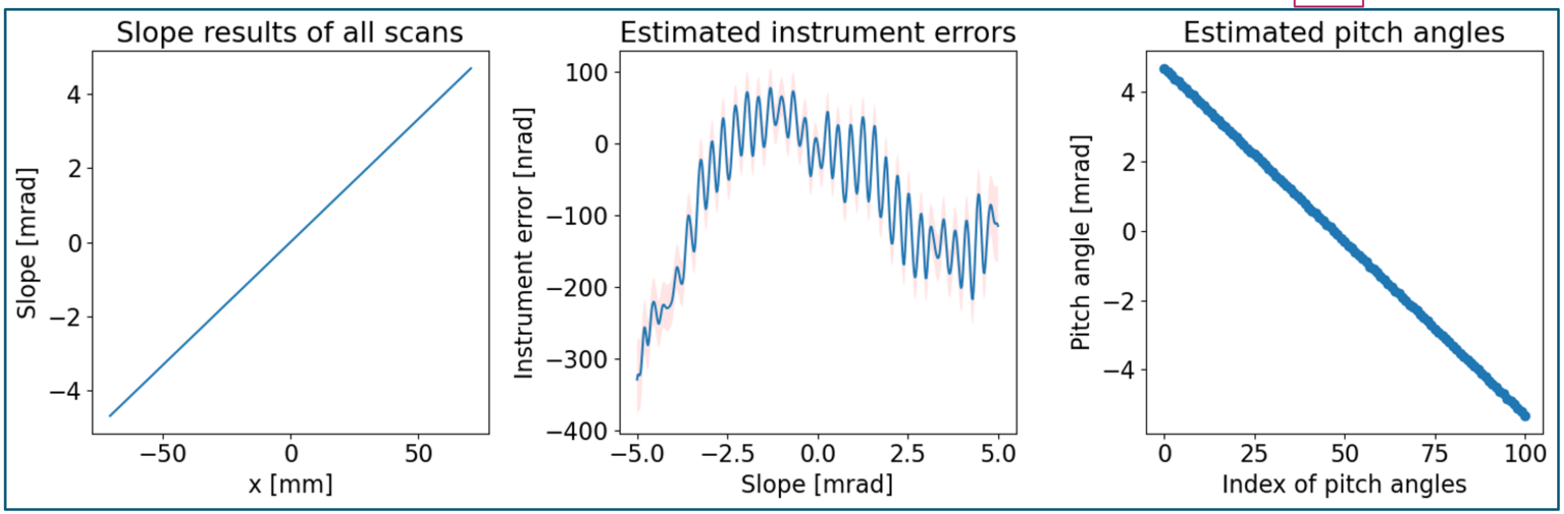
$$\hat{\boldsymbol{c}}_m, \hat{\boldsymbol{c}}_e, \hat{\boldsymbol{\alpha}} = \underset{\boldsymbol{c}_m, \boldsymbol{c}_e, \boldsymbol{\alpha}}{\arg\min} \sum_{n=0}^{N-1} \sum_{x_w} \left(s_n(x_w) + r_n(x_w) - \boldsymbol{M}\big(x_m(x_w, \alpha_n)\big)\, \boldsymbol{c}_m - \boldsymbol{E}\big(s_n(x_w)\big)\, \boldsymbol{c}_e - \alpha_n \right)^2$$

$$s.t. \quad \alpha_0 = 0, \quad \boldsymbol{E}(0)\,\boldsymbol{c}_e = 0, \quad \boldsymbol{s}^{\top}\,\boldsymbol{E}(\boldsymbol{s})\,\boldsymbol{c}_e = 0.$$



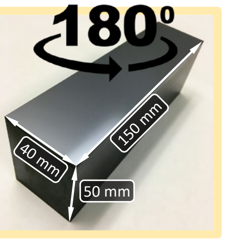


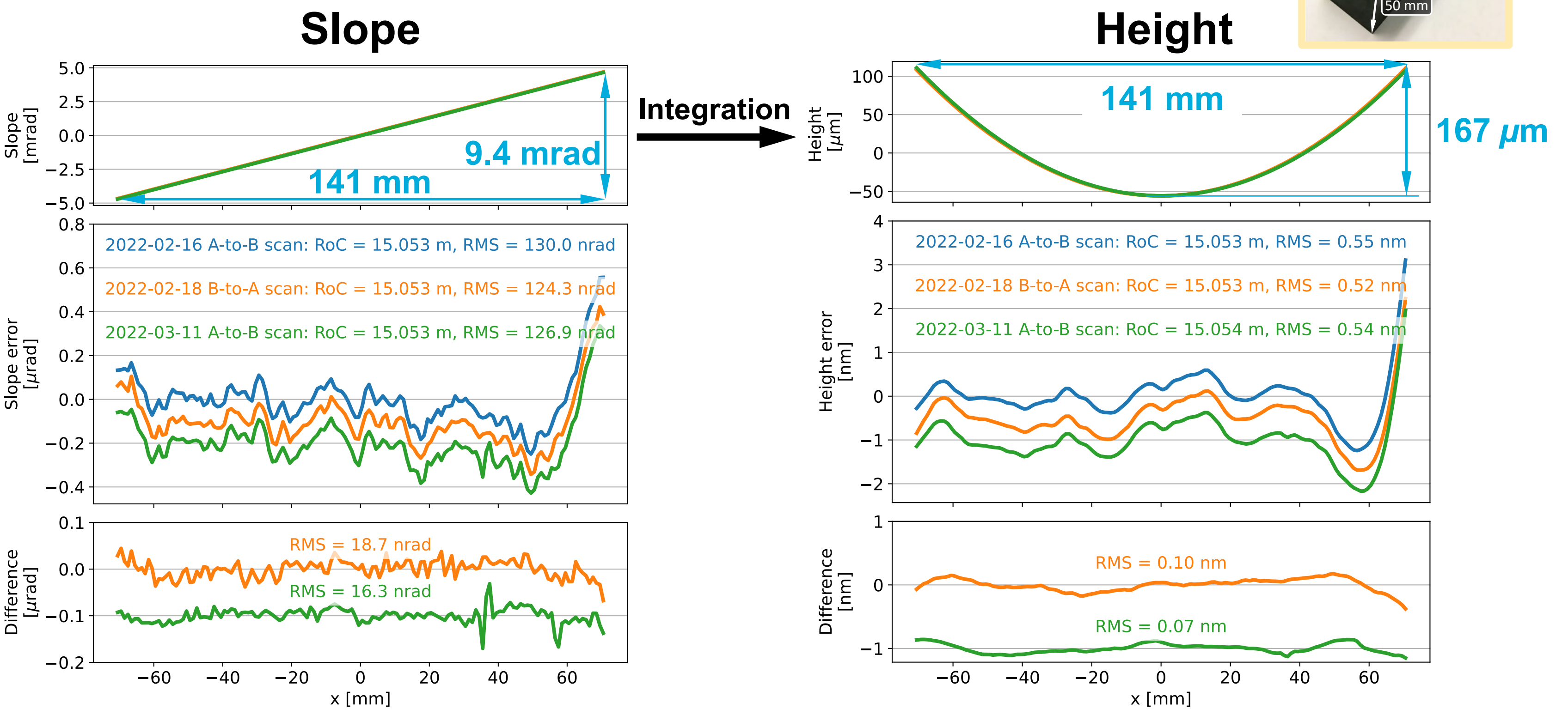
$\hat{\boldsymbol{m}}(x_m) = \boldsymbol{M}(x_m)\hat{\boldsymbol{c}}_m$ $\quad$ $\hat{\boldsymbol{e}}(s) = \boldsymbol{E}(s)\hat{\boldsymbol{c}}_e$ $\quad$ $\hat{\boldsymbol{\alpha}}$



Huang L, Wang T, Nicolas J, Polack F, Zuo C, Nakhoda K, et al. Multi-pitch self-calibration measurement using a nano-accuracy surface profiler for X-ray mirror metrology. Opt Express (2020)

Compare A-to-B and B-to-A scans

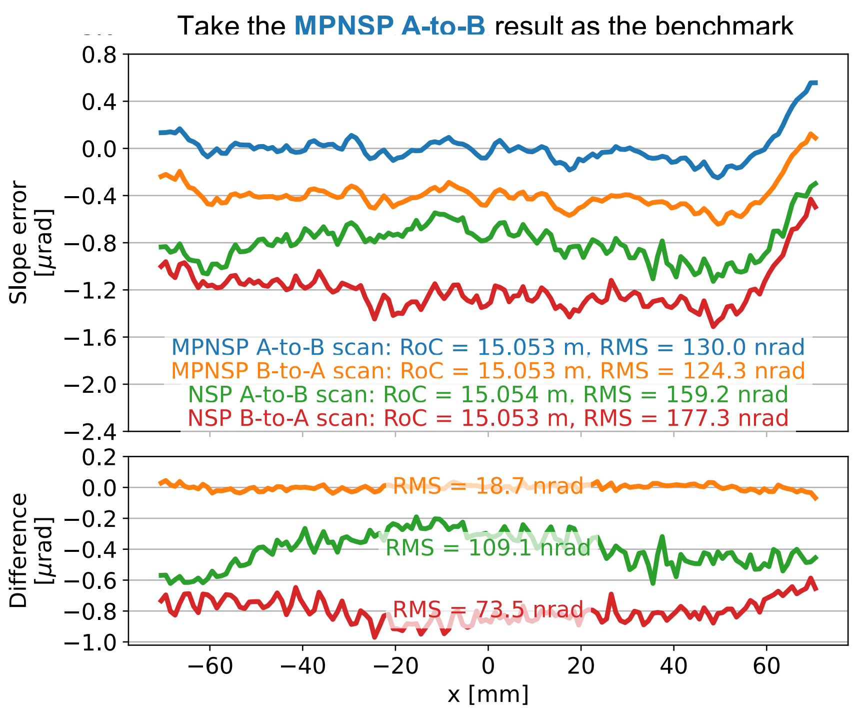




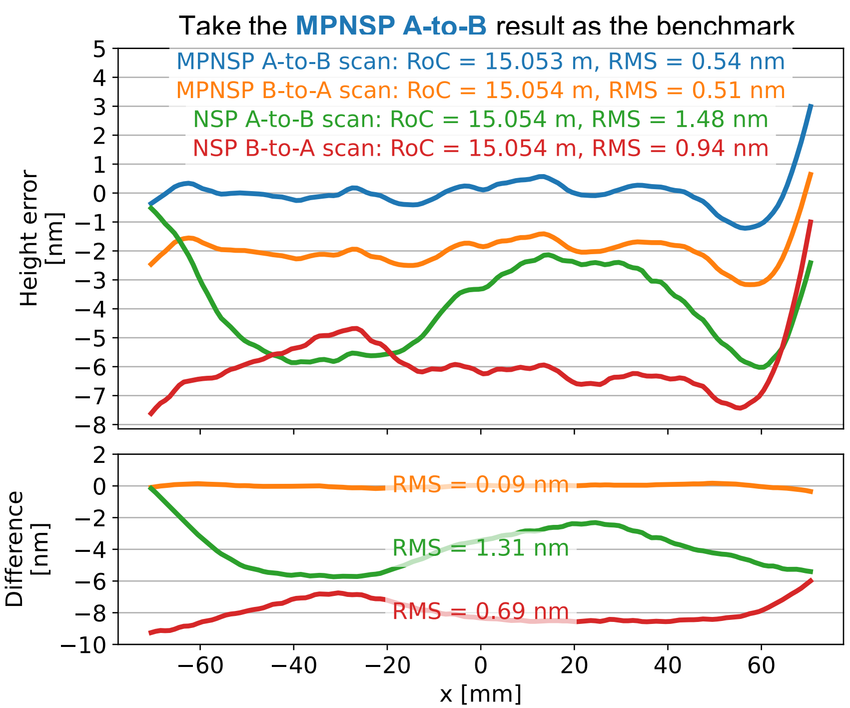
The A-to-B and B-to-A scans show excellent self-consistency!

Facility Improvement: compare MPNSP and NSP results

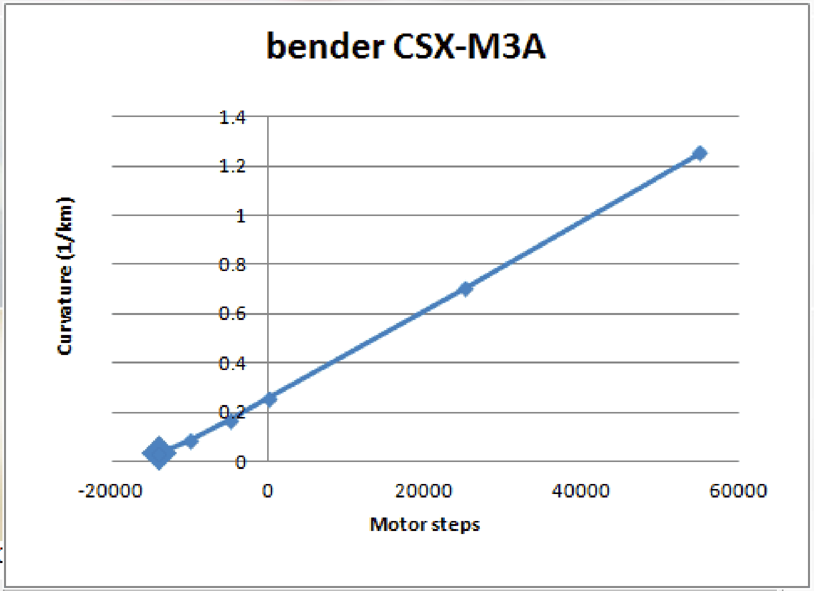
Slope residuals

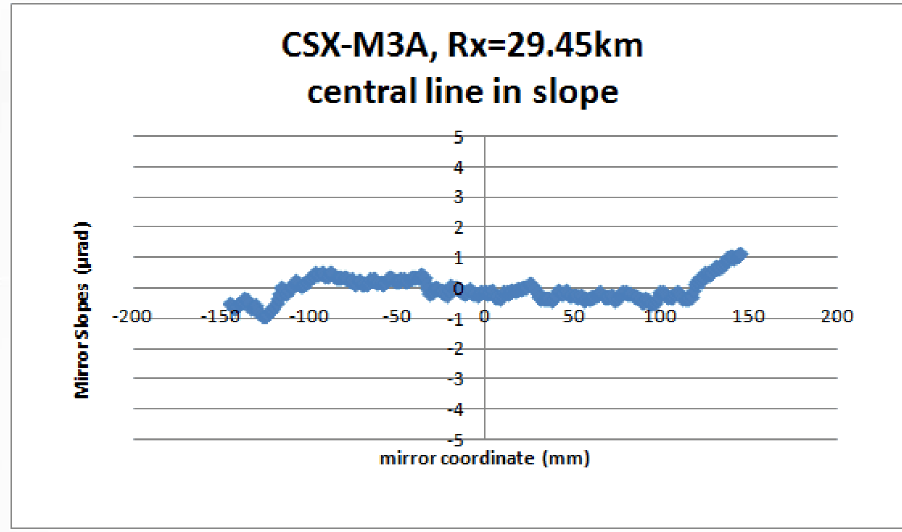


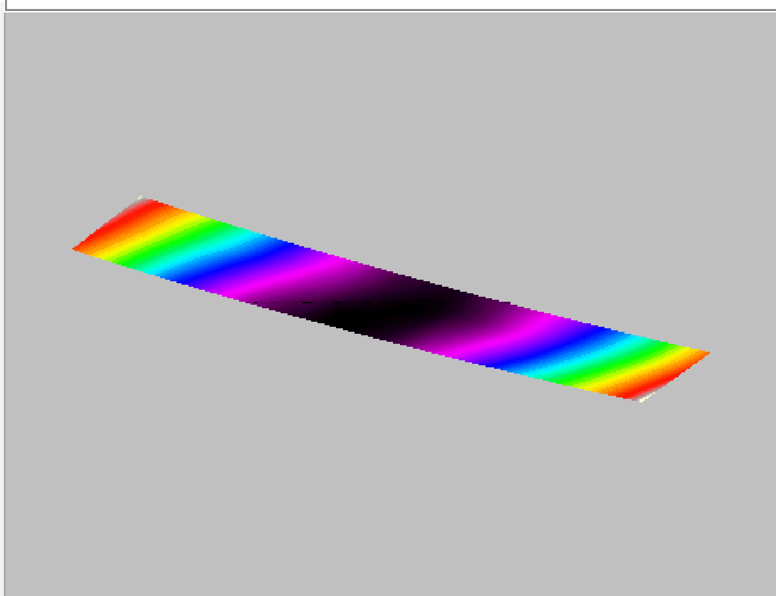
Height residuals

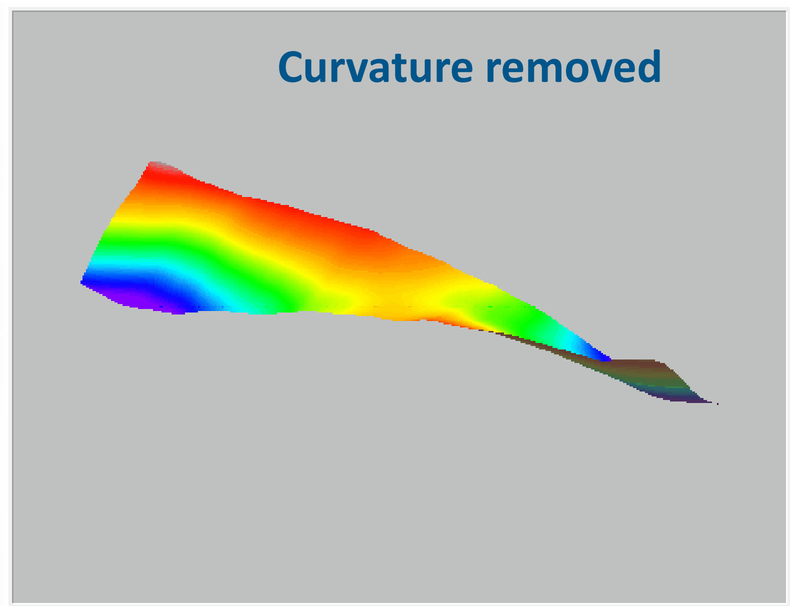


Why do we need 2D information?

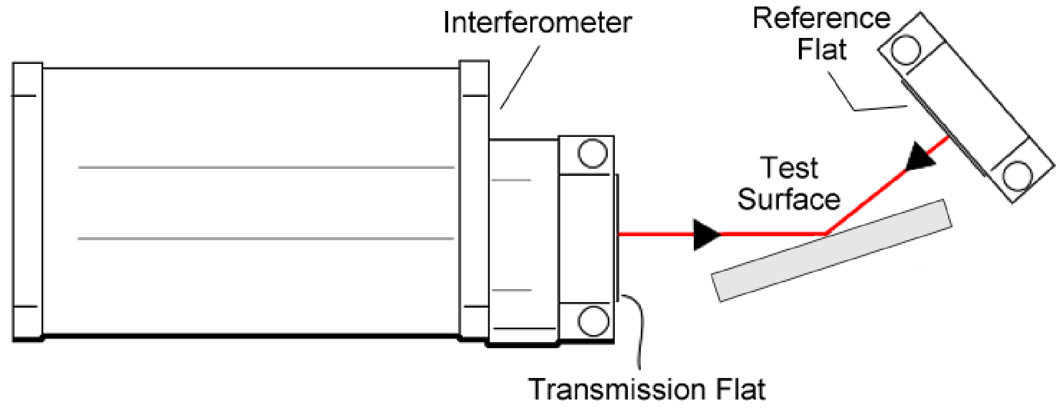




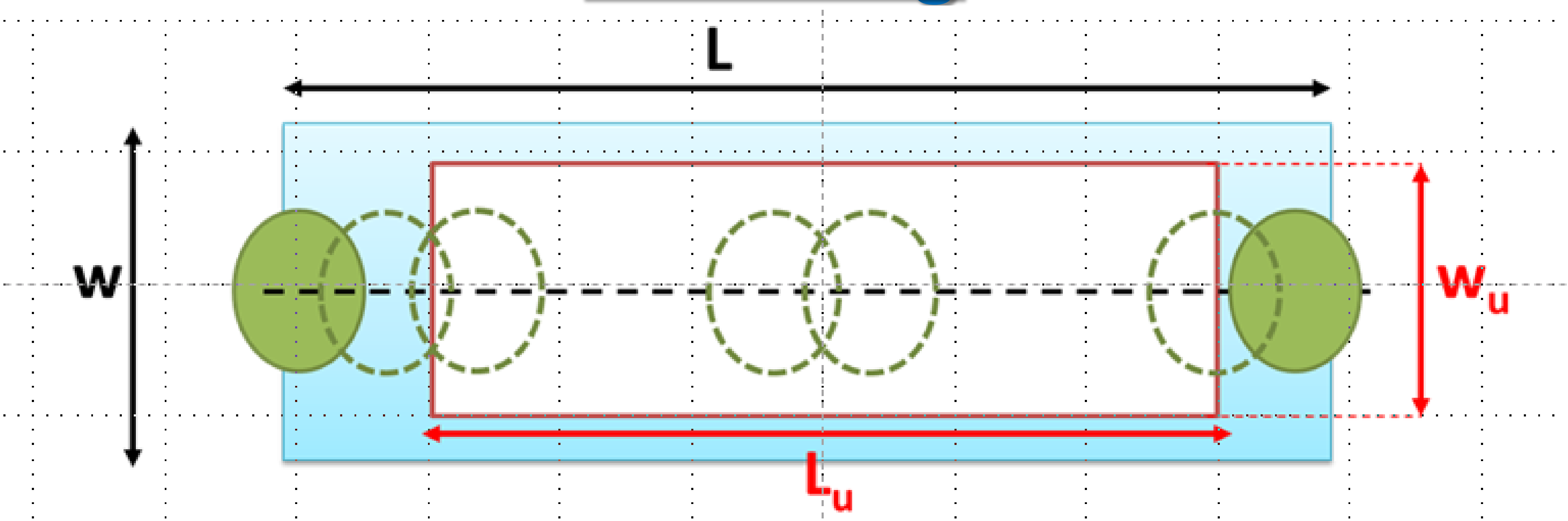




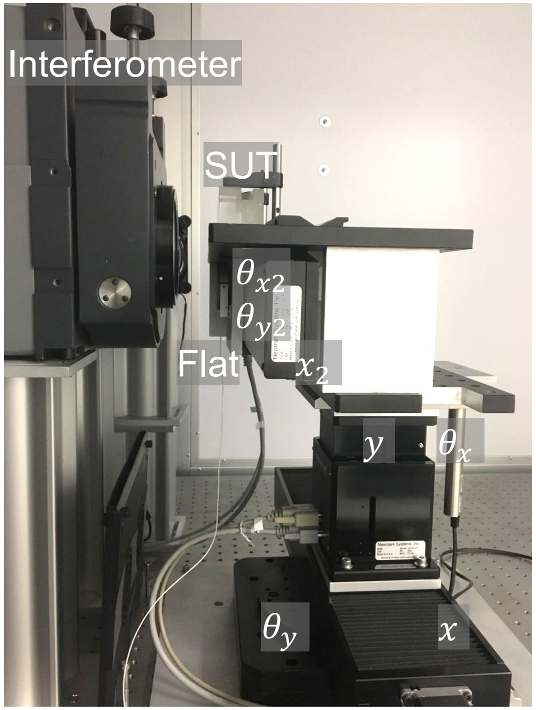
Grazing Incidence Interferometry

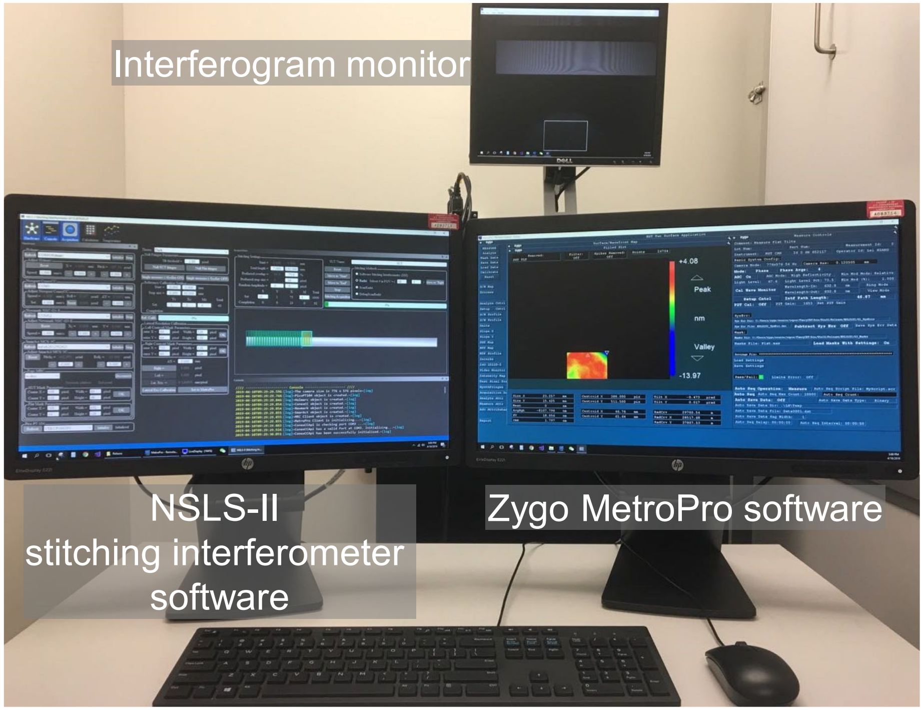


Stitching



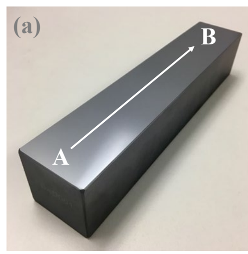
The 2D stitching interferometer prototype



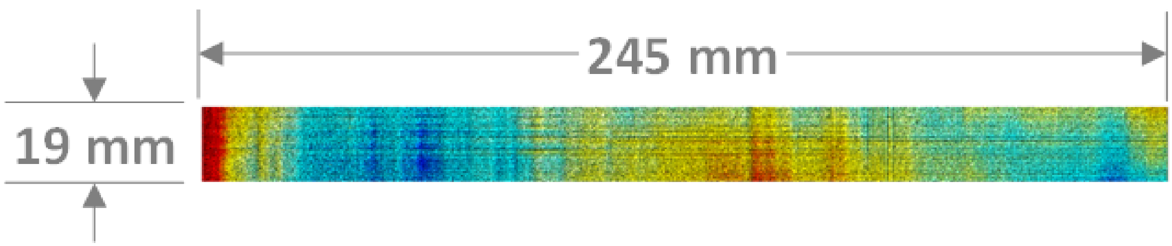


L. Huang, T. Wang, K. Tayabaly, D. Kuhne, W. Xu, W. Xu, M. Vescovi, and M. Idir, "Stitching interferometry for synchrotron mirror metrology at National Synchrotron Light Source II (NSLS-II)," Optics and Lasers in Engineering 124, 105795 (2020).

The 2D stitching interferometer prototype



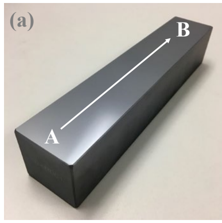
JTEC flat mirror
Dimensions: 250mm (L) × 50mm (W) × 50mm (H)
Clear aperture: 245mm (L) × 26mm (W)



0.59 nm RMS

L. Huang, T. Wang, K. Tayabaly, D. Kuhne, W. Xu, W. Xu, M. Vescovi, and M. Idir, "Stitching interferometry for synchrotron mirror metrology at National Synchrotron Light Source II (NSLS-II)," Optics and Lasers in Engineering 124, 105795 (2020).

Repeatability



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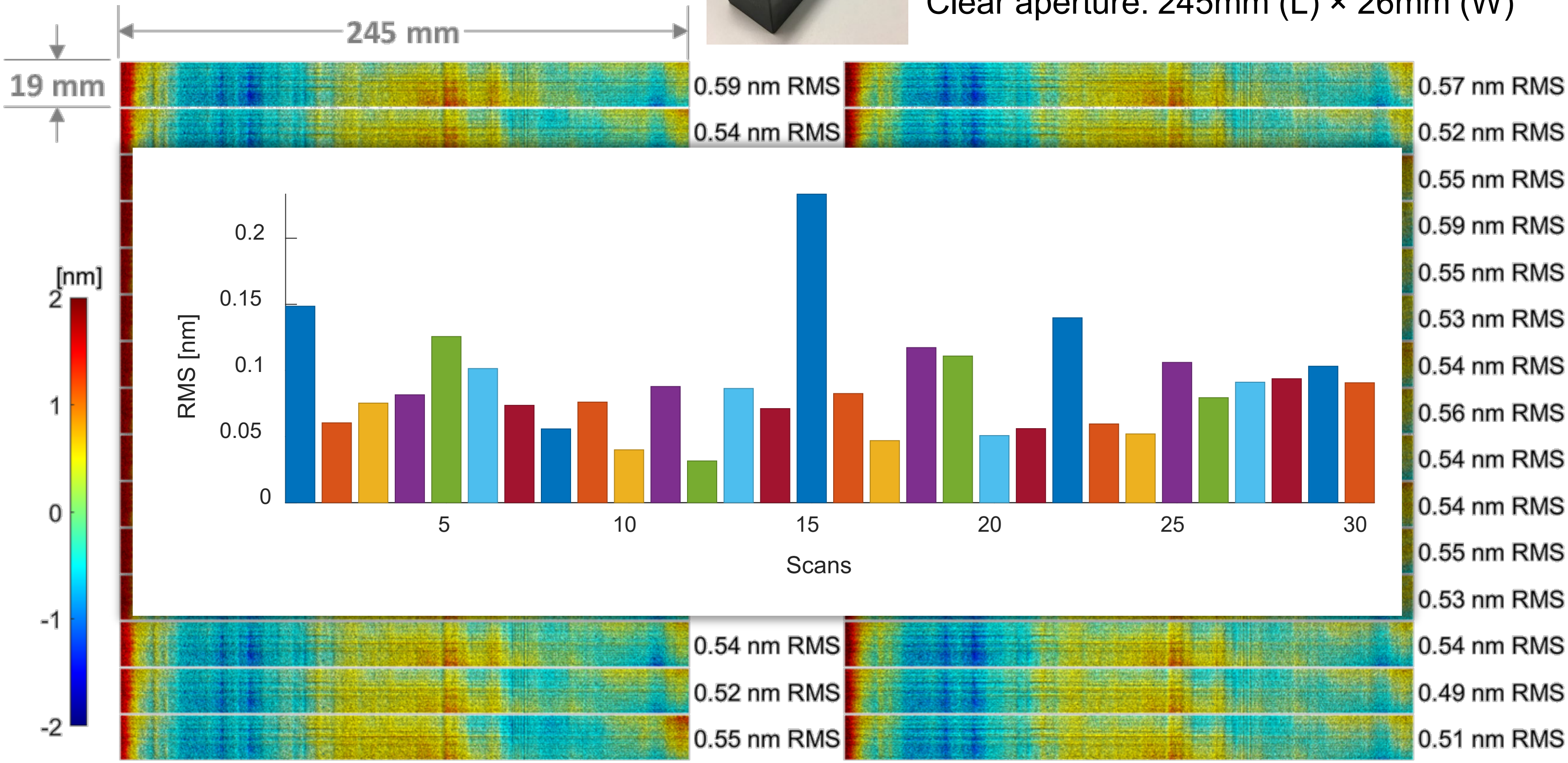

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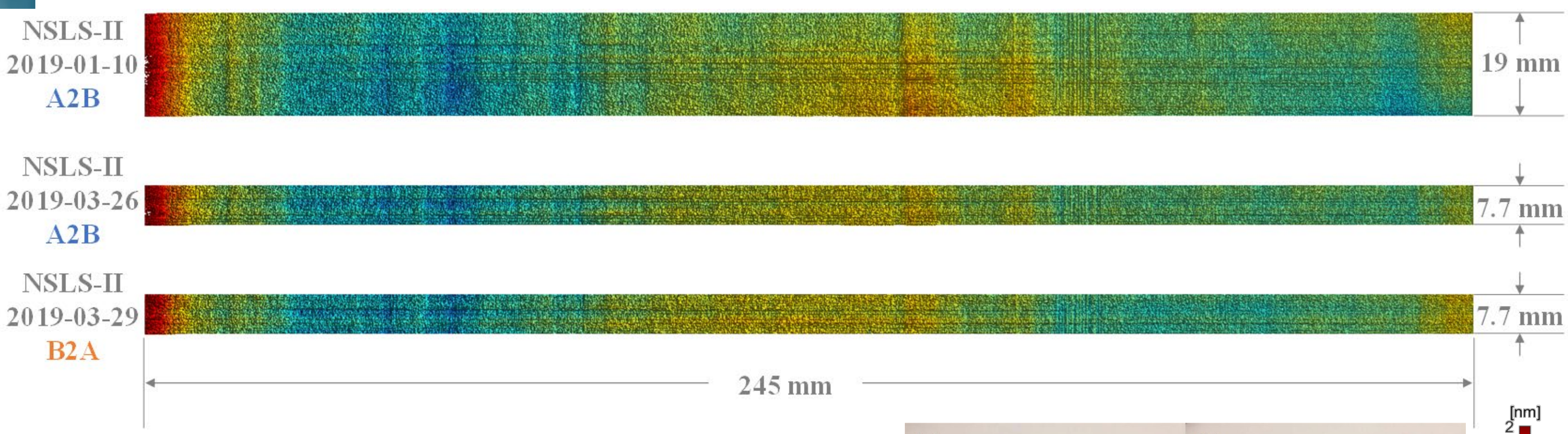
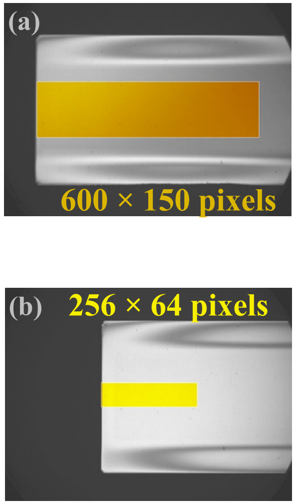
Check the self consistency





JTEC flat mirror
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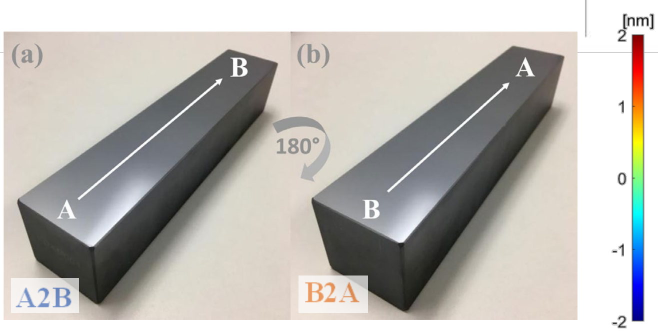
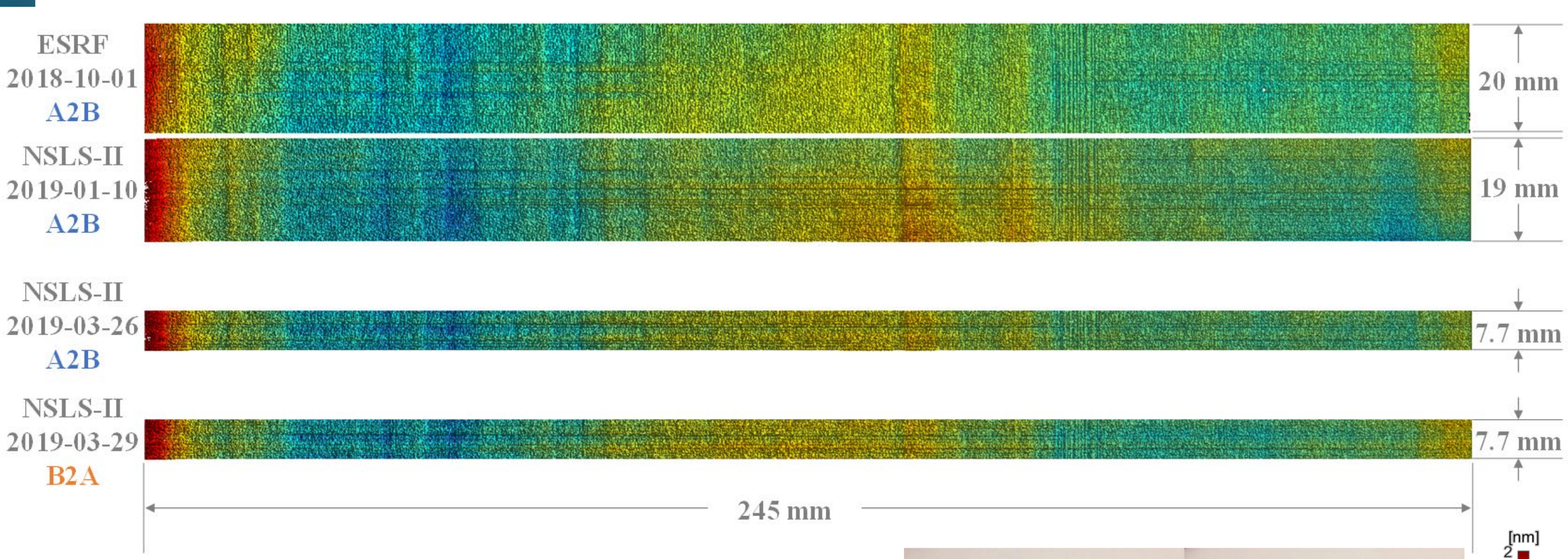
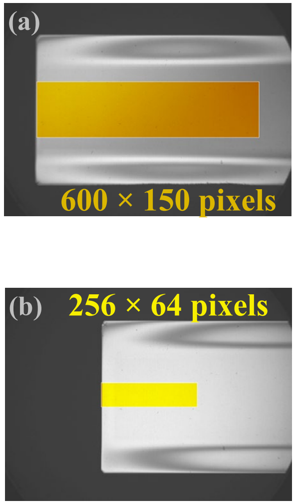
Clear aperture: 245mm (L) × 26mm (W)



Comparison with ESRF stitching results in height





JTEC flat mirror
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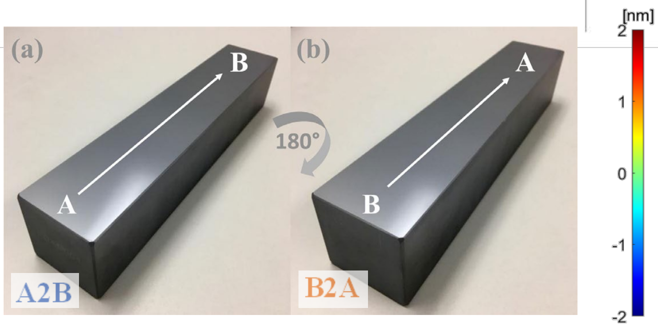
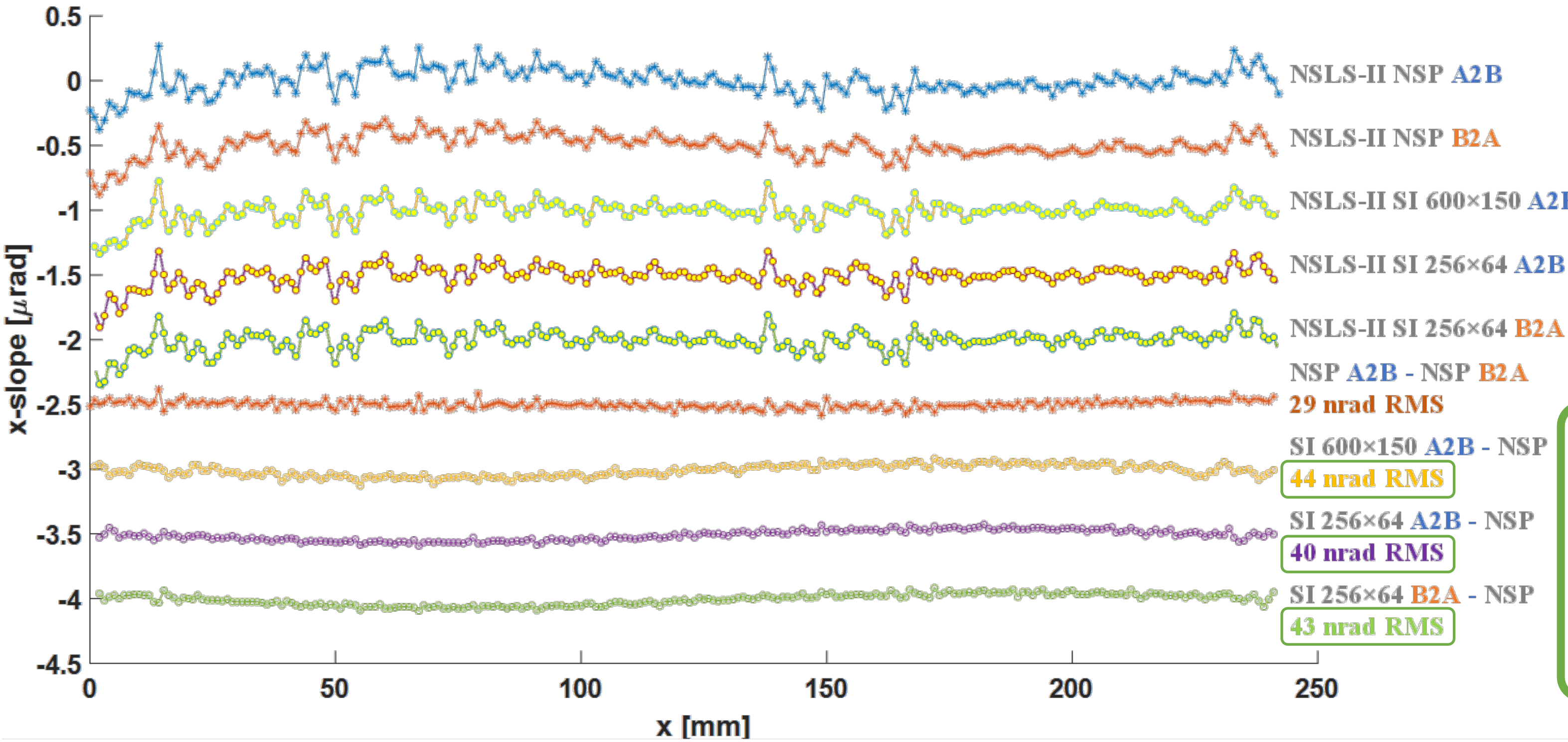
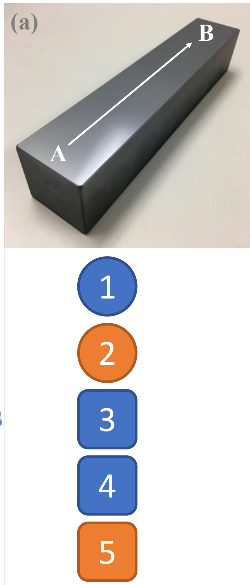
Clear aperture: 245mm (L) × 26mm (W)



Comparison with NSLS-II NSP in slope



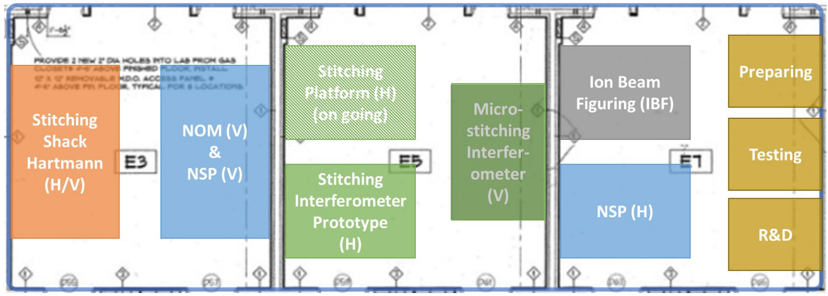


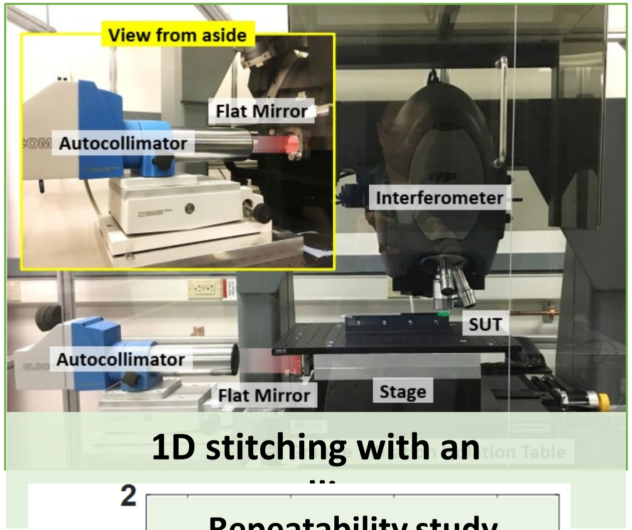
All differences between these measurements are below **50 nrad RMS**

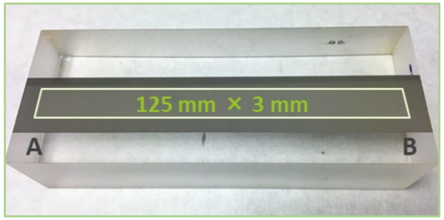
L. Huang, T. Wang, K. Tayabaly, D. Kuhne, W. Xu, W. Xu, M. Vescovi, and M. Idir, "Stitching interferometry for synchrotron mirror metrology at National Synchrotron Light Source II (NSLS-II)," Optics and Lasers in Engineering 124, 105795 (2020).

Micro-stitching interferometry

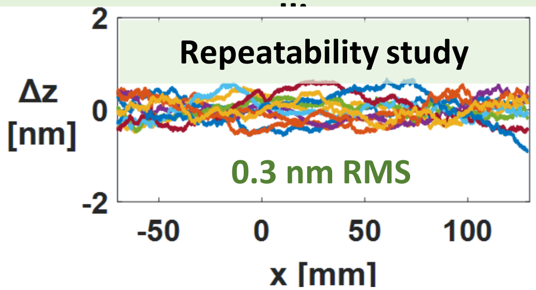
1D stitching with angular measurement

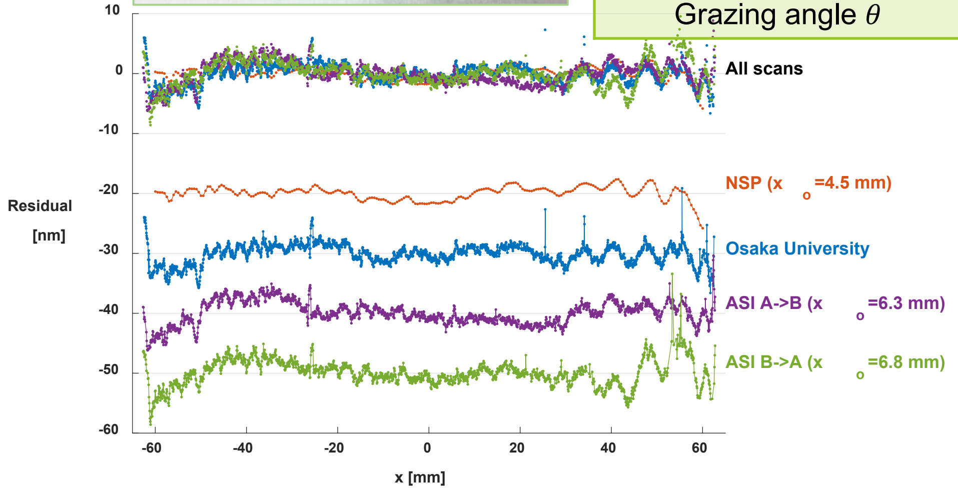






Target ellipse	
Source-to-mirror distance p	$45.170\ m$
Mirror-to-focus distance q	$331.92\ mm$
Grazing angle θ	$2.8\ mrad$





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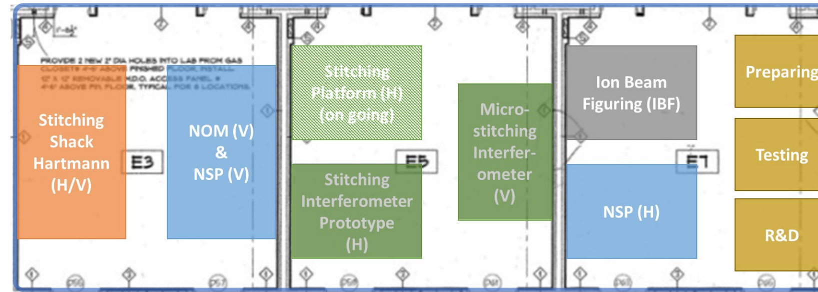
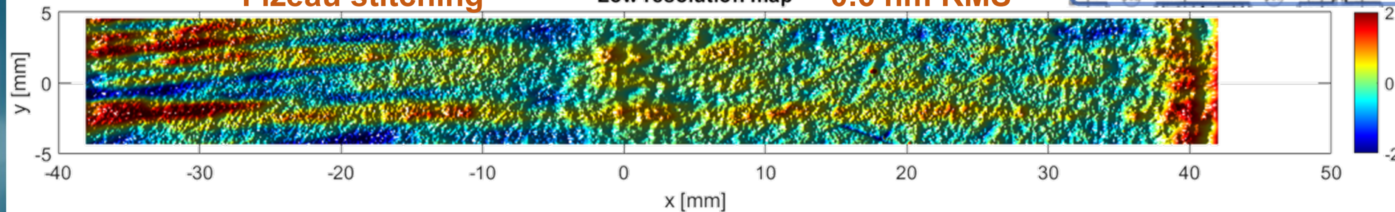
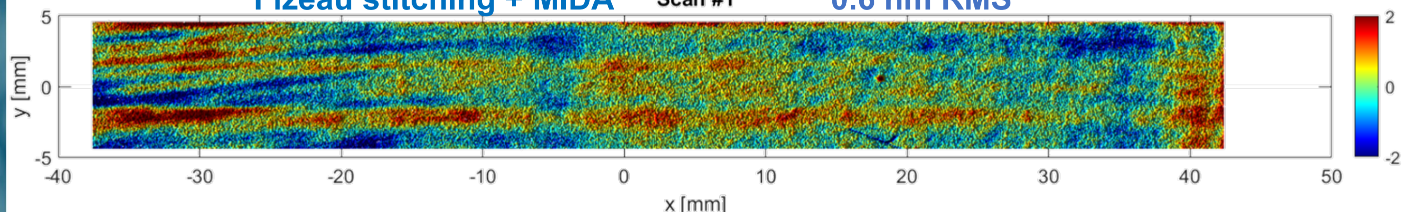
Microscopic Interferometer Data Analyzer (MIDA)



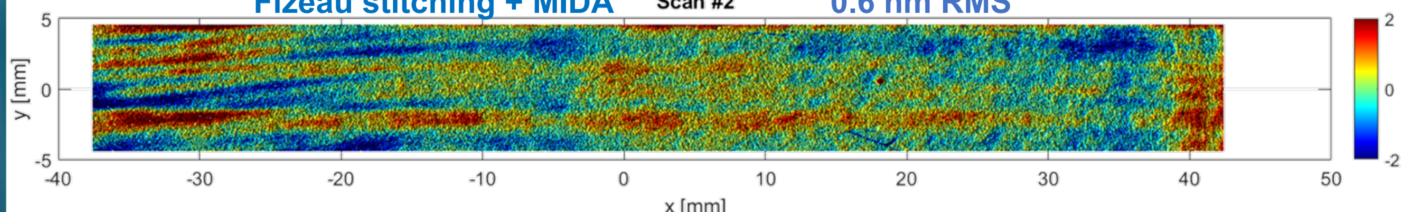
Fizeau stitching Low resolution map **0.6 nm RMS**



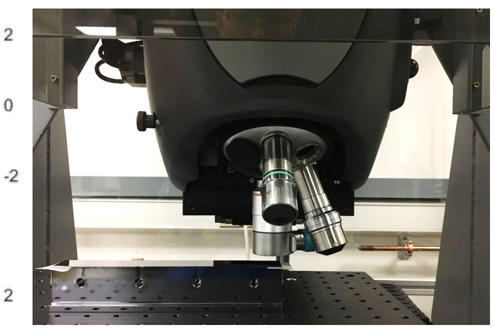
Fizeau stitching + MIDA Scan #1 **0.6 nm RMS**



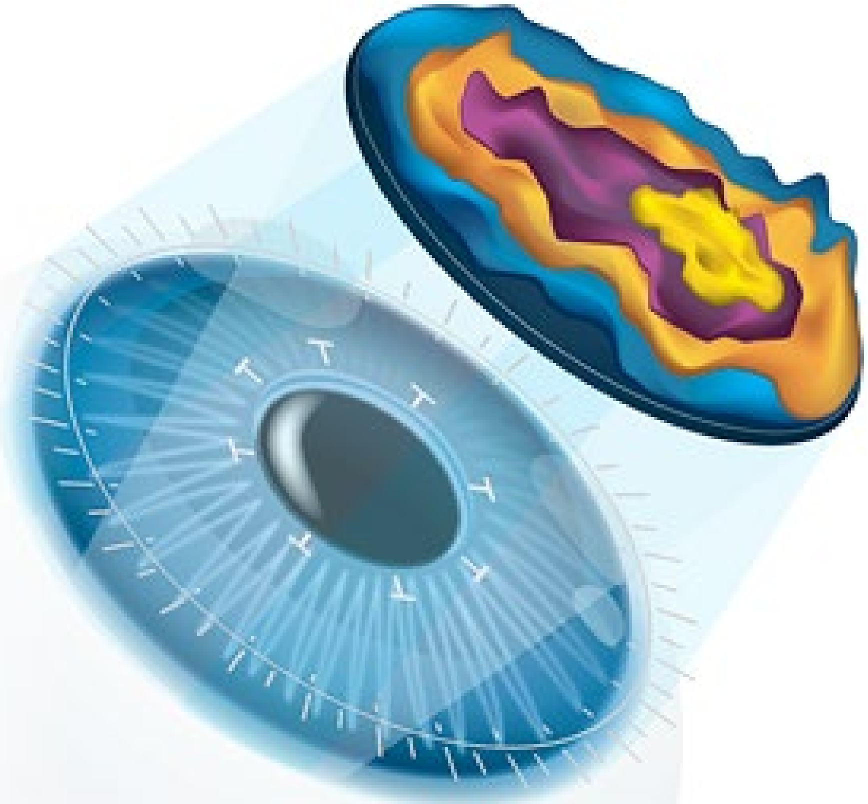
Fizeau stitching + MIDA Scan #2 **0.6 nm RMS**



Target ellipse parameters	
p	$30\ m$
q	$0.3\ m$
θ	$3\ mrad$



Combination of the microscopic data and the Fizeau stitching data



Surgery

Lenses or Glasses

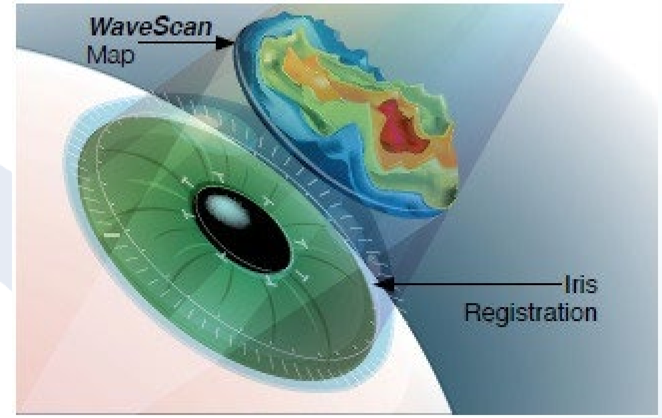
Wavefront-guided LASIK = **Surgery**

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.

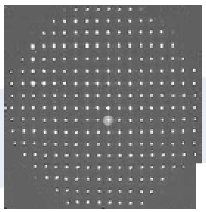
Wikipedia

Wavefront-guided LASIK

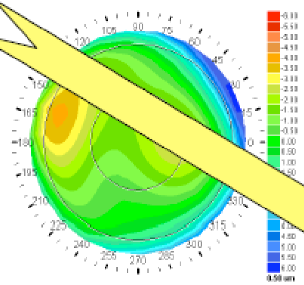


IROC

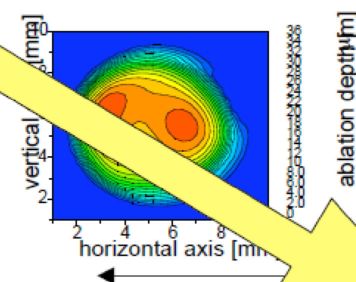
The problem



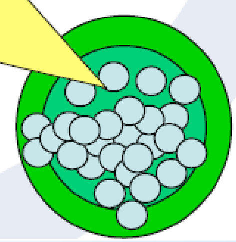
Aberration measurements



Wavefront reconstruction

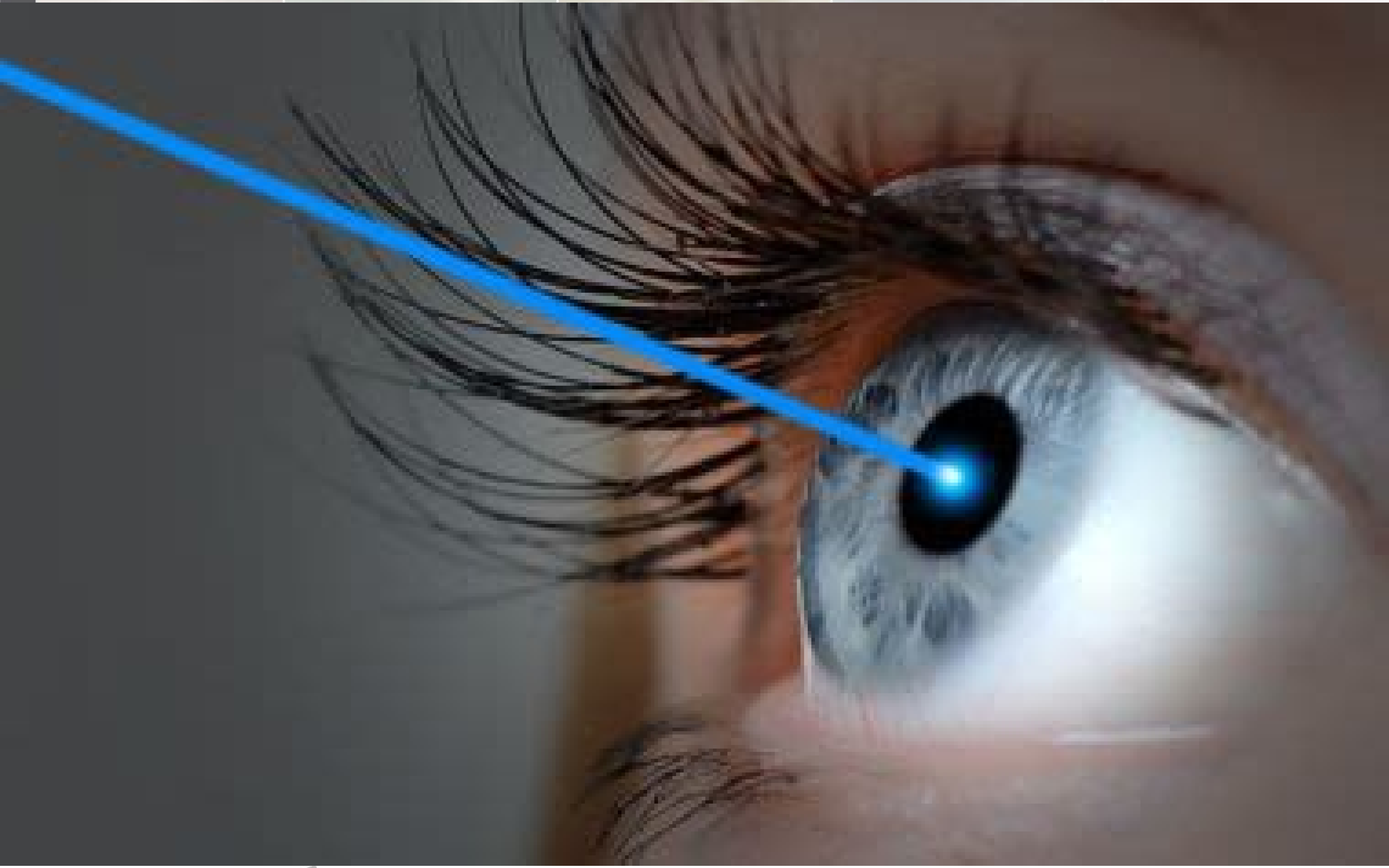


Ablation profile calculations

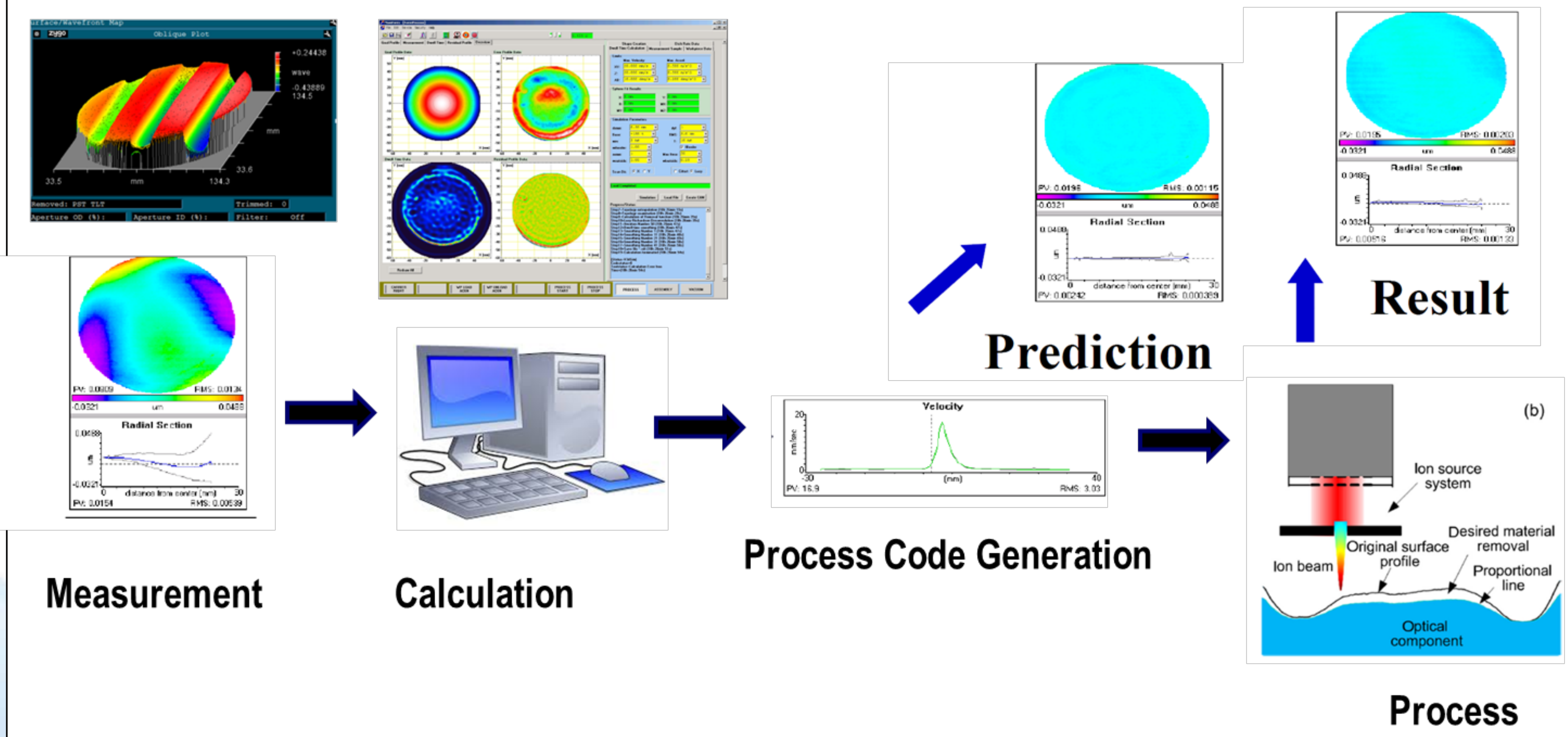


spot calculations & ablation

Wavefront-guided LASIK
Laser-Assisted In Situ Keratomileusis



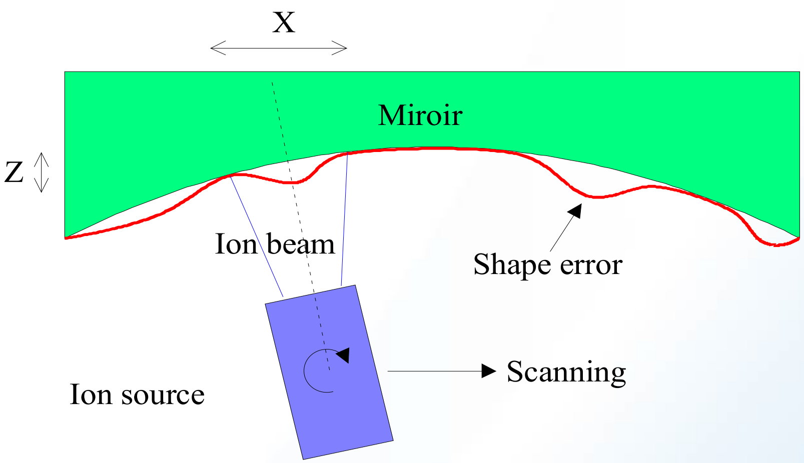
Ion Beam Polishing
Step by Step



R&D : Ion Beam Polishing

Internal NSLS II Collaboration : optical Metrology and Optical Fabrication Groups

Ion Beam Figuring (IBF)

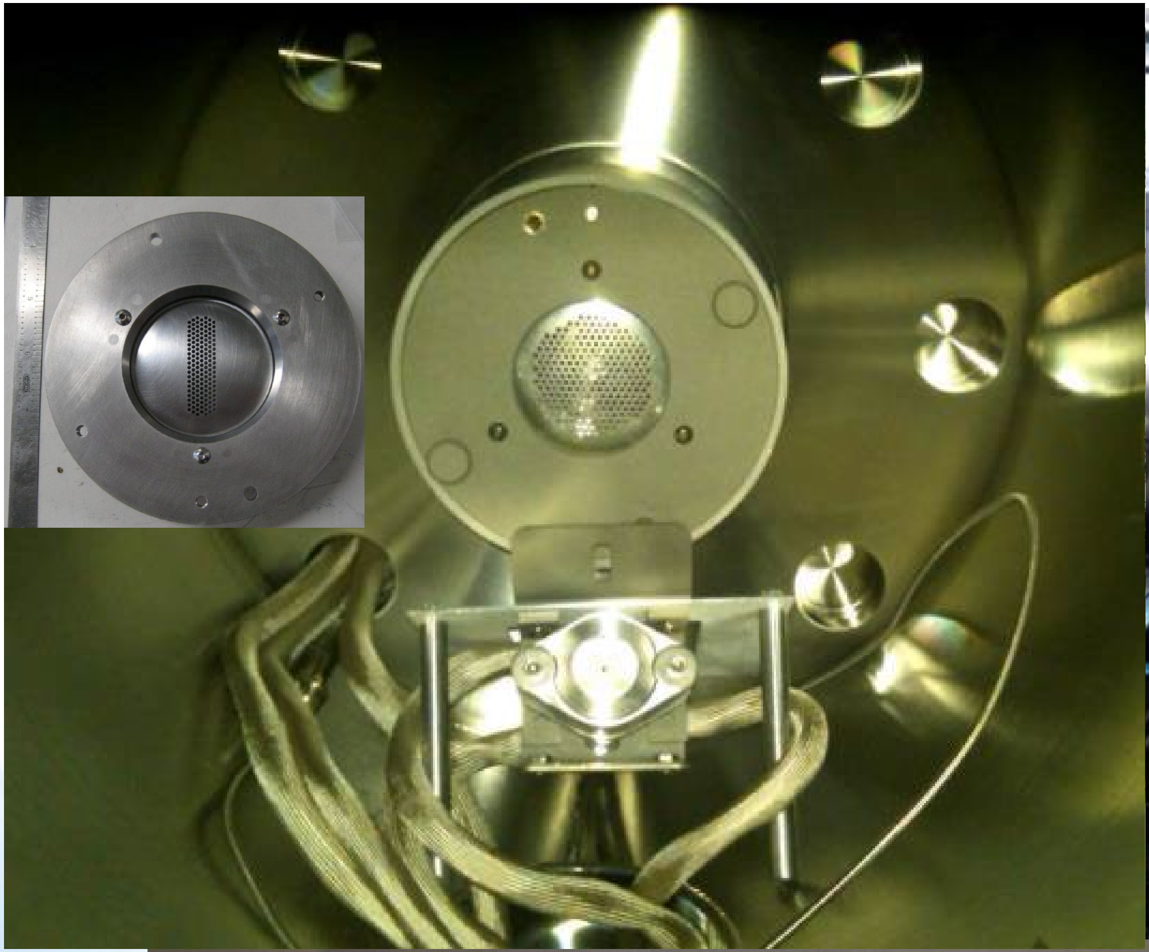


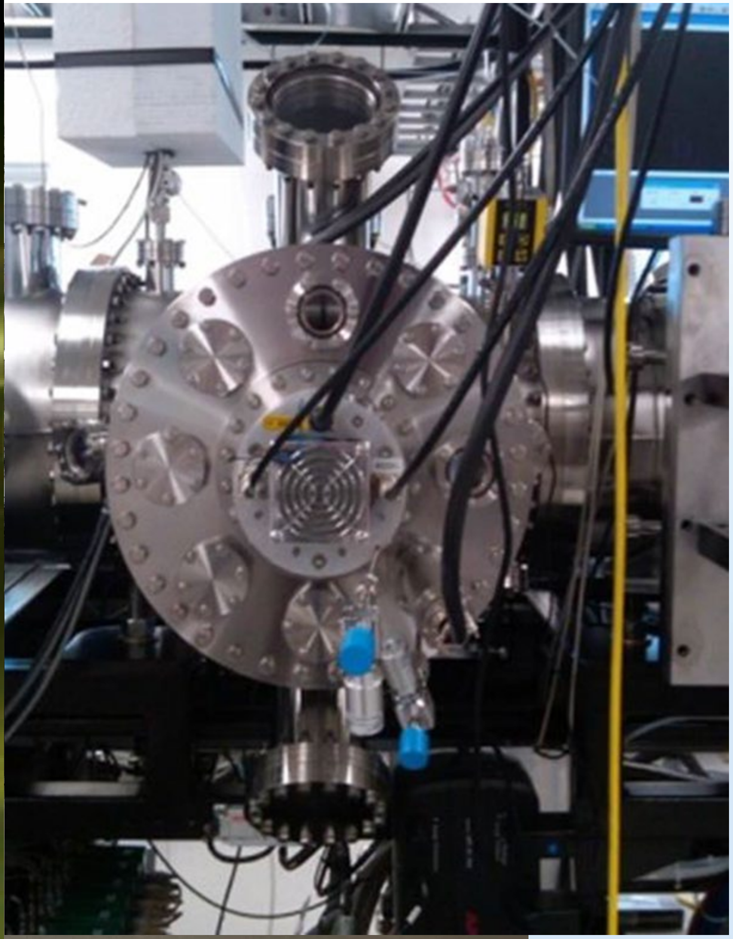
- Last step in figuring/polishing process of optics
- Sputtering of unwanted material
- Correction of long spatial wavelengths (X ~ cm)
- Correction of small thickness (Z < μm)

R&D : Ion Beam Polishing

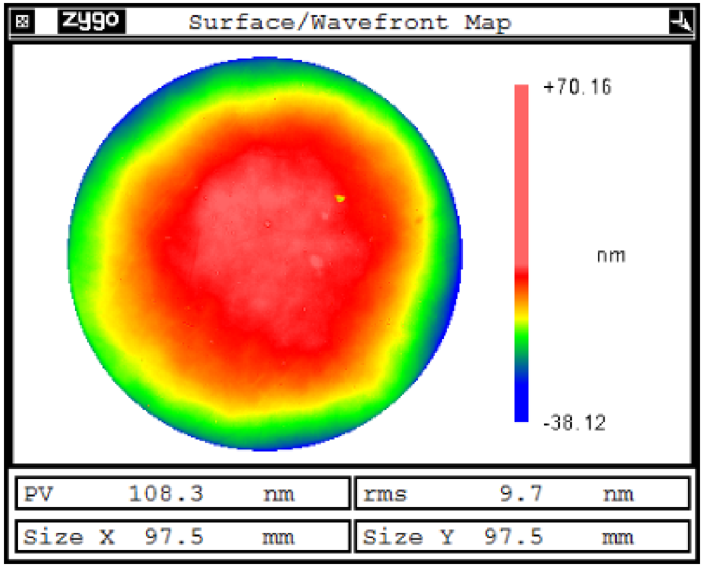
Internal NSLS II Collaboration : optical Metrology and Optical Fabrication Groups

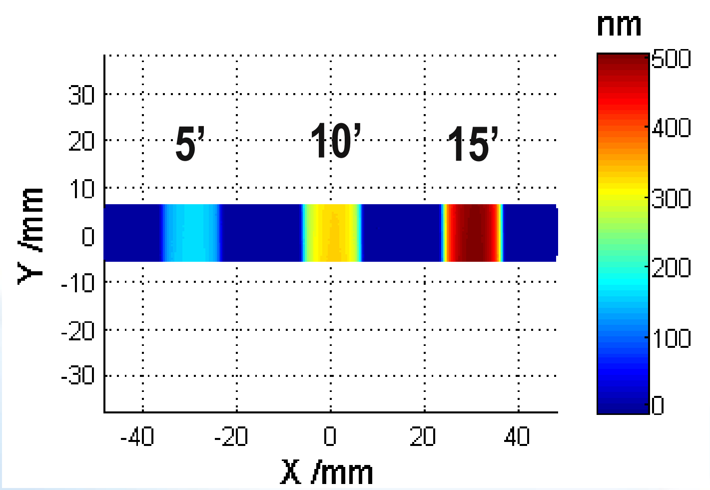
Ion Beam Figuring (IBF)



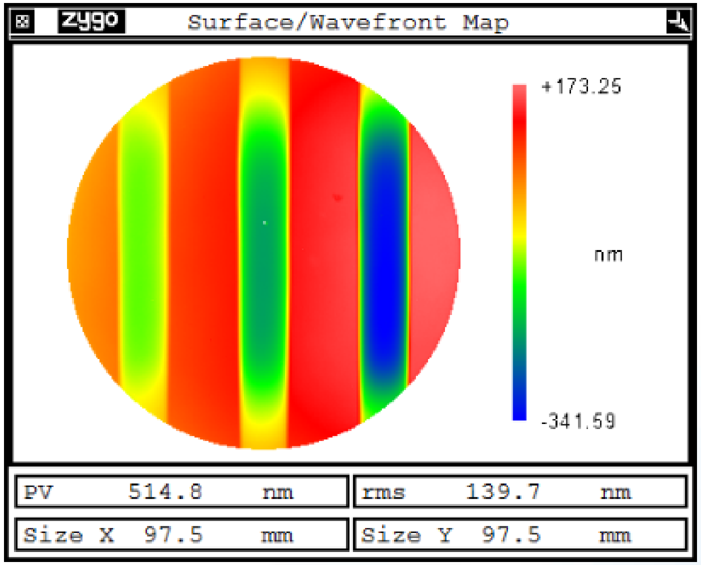


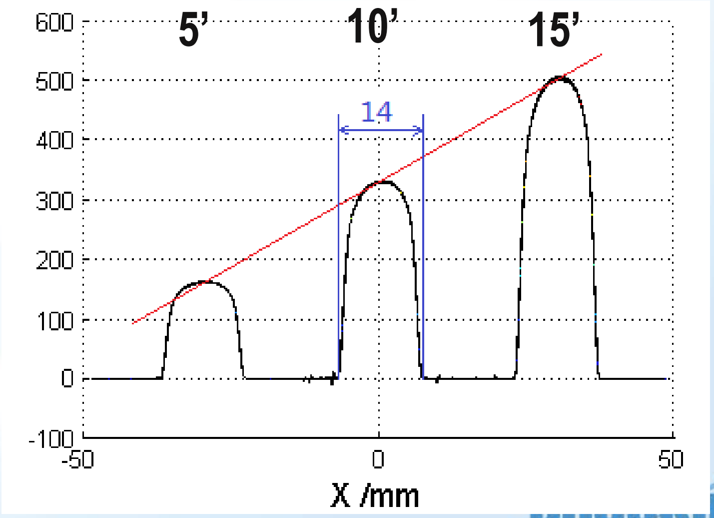
Before IBF





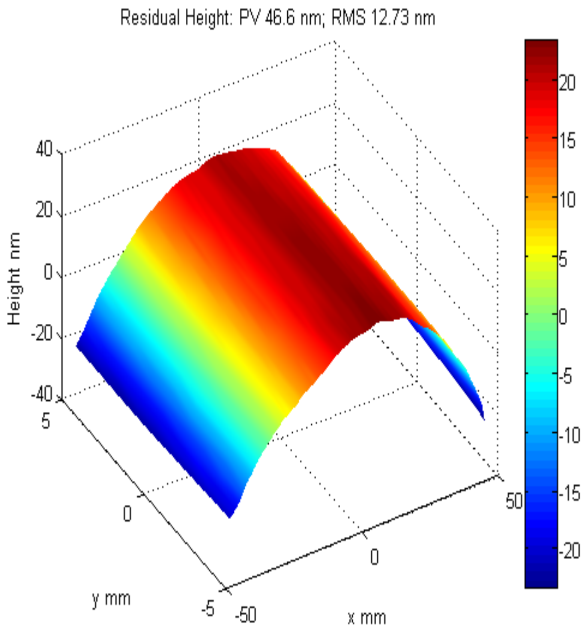
After IBF





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

Plane sample #1

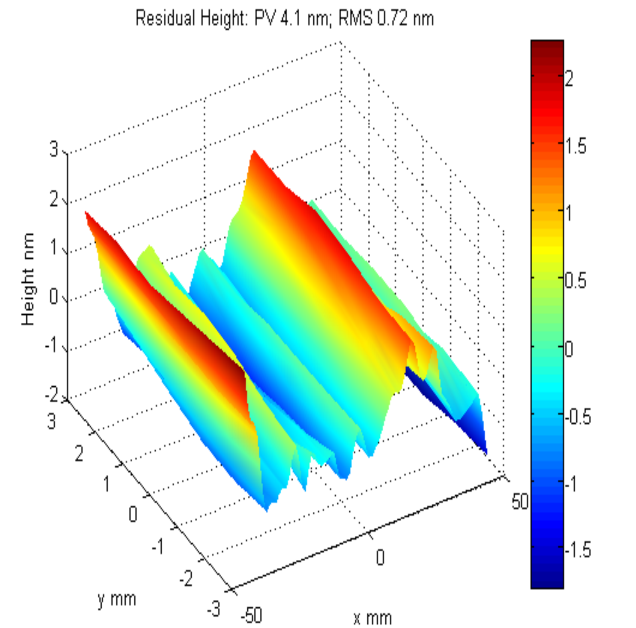


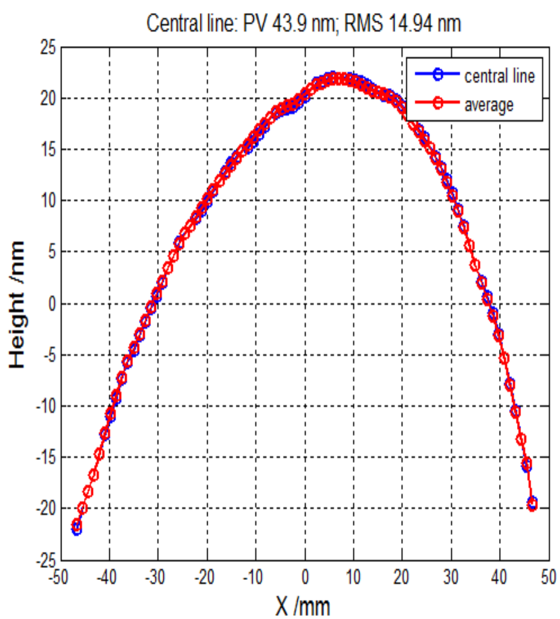
$\lambda/14$ ~ 300$

~ 44 nm PV
RMS: 15 nm

1D IBF

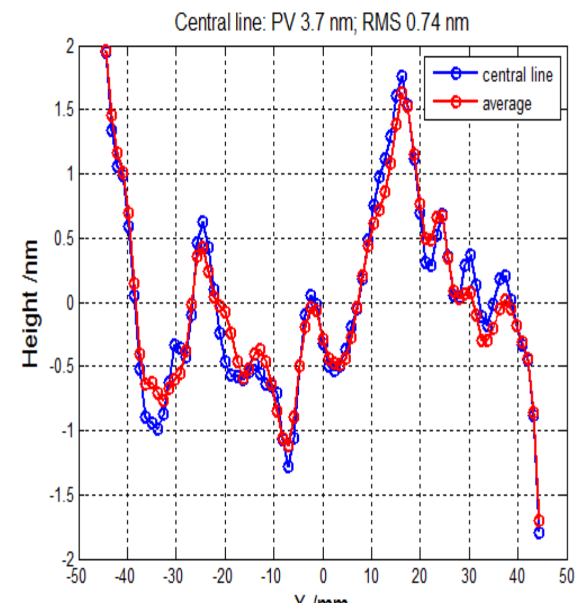
9 minutes





~ 3.7 nm PV
RMS: 0.74 nm

$\lambda/171$ ~ 3000$

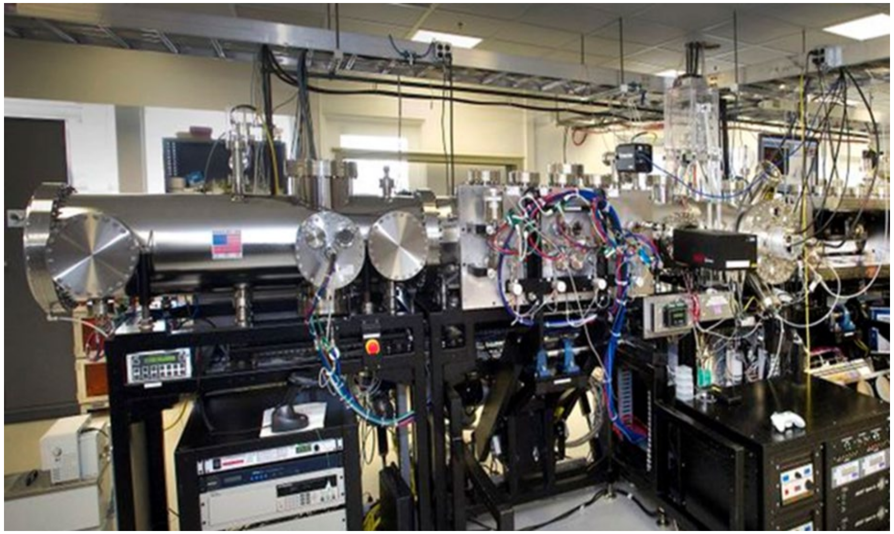


LDRD: Diffraction-limited and wavefront preserving reflective optics development

Mourad Idir (PI), Lei Huang (Co-PI), Nathalie Bouet (Co-PI)

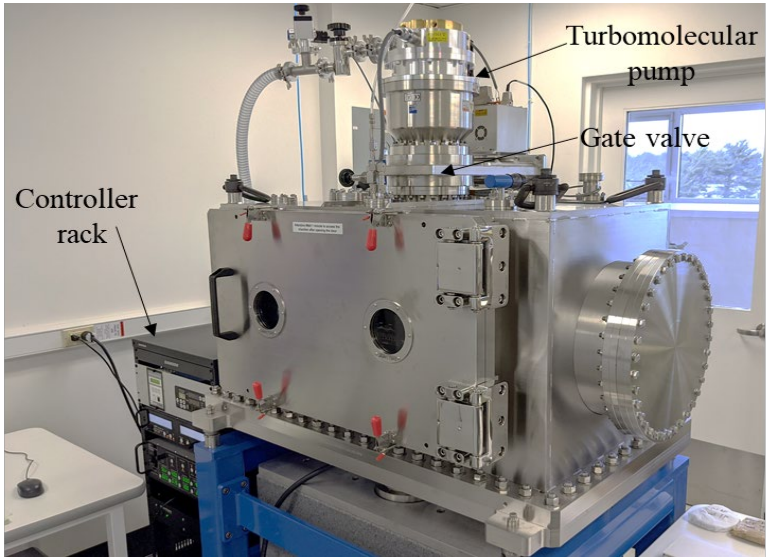
Tianyi Wang (Post Doc), Matthew Vescovi, Yi Zhu, Dennis Khune

Improved the 1D-IBF system



1D-IBF system

Developed the 2D-IBF system



2D-IBF system

35

Diffraction-limited reflective optics development at NSLS-II

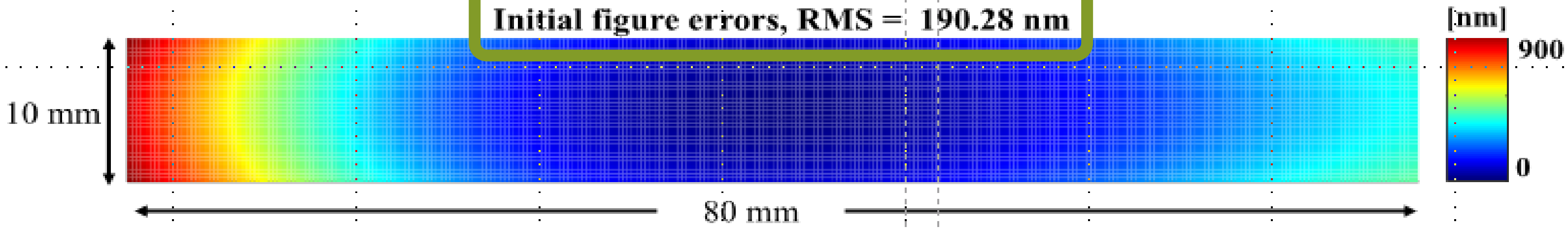
Few Examples

Example 1

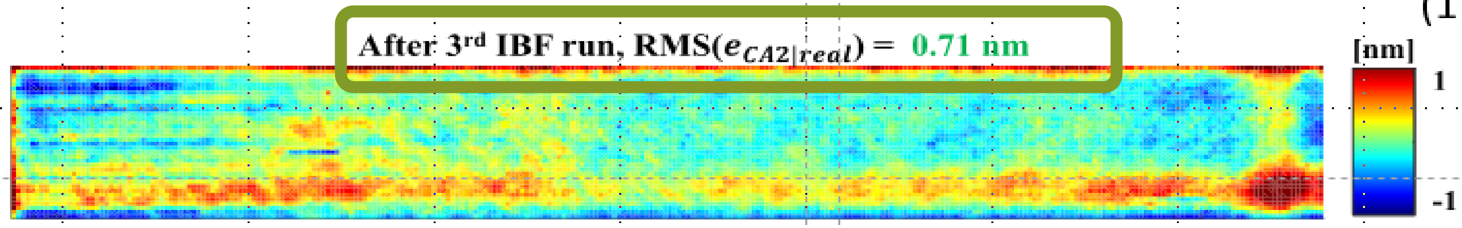
Elliptic cylinders using NSLSII IBF System

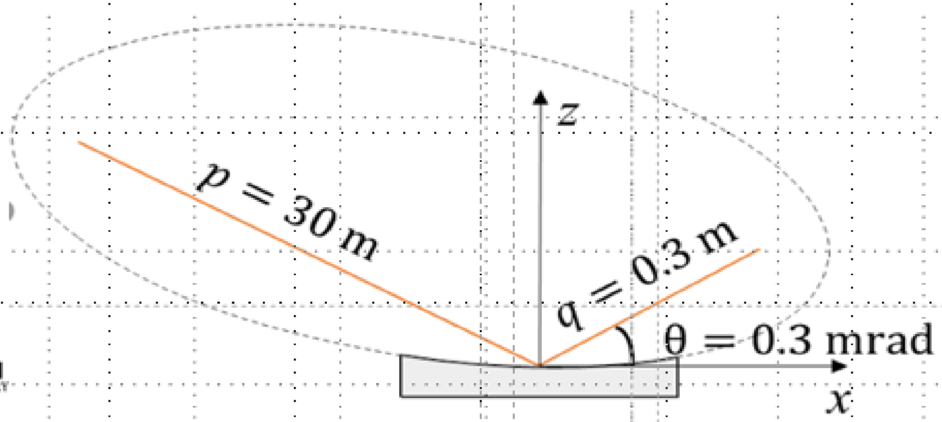
Figure error map of the mirror (relative to intended ellipse)

Starting mirror (sphere)



Finished mirror (1D ellipse)

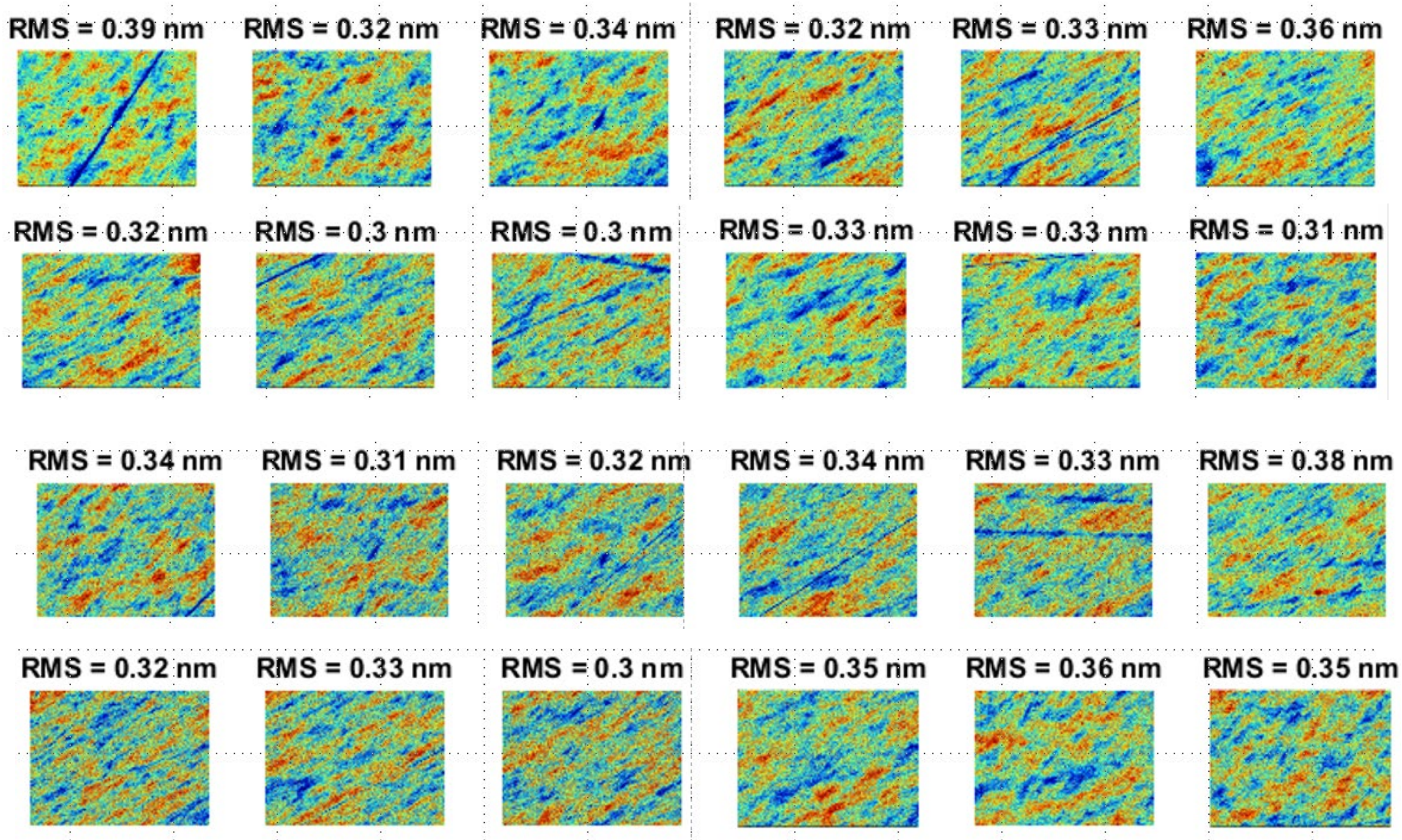




The Surface roughness not affected by the IBF process

Before IBF

After IBF



Example 2 FLAT Grating (ALS)

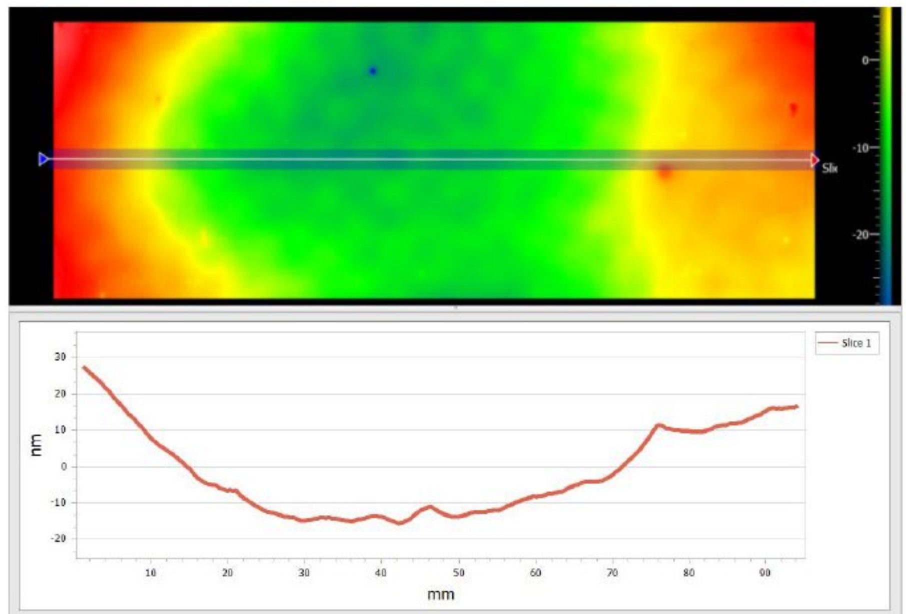
Low blaze angle grating #C11 for IBF tests

- 200 lines/mm
- Blaze angle 0.22°

100 mm x 40 mm x 20 mm

Goals:

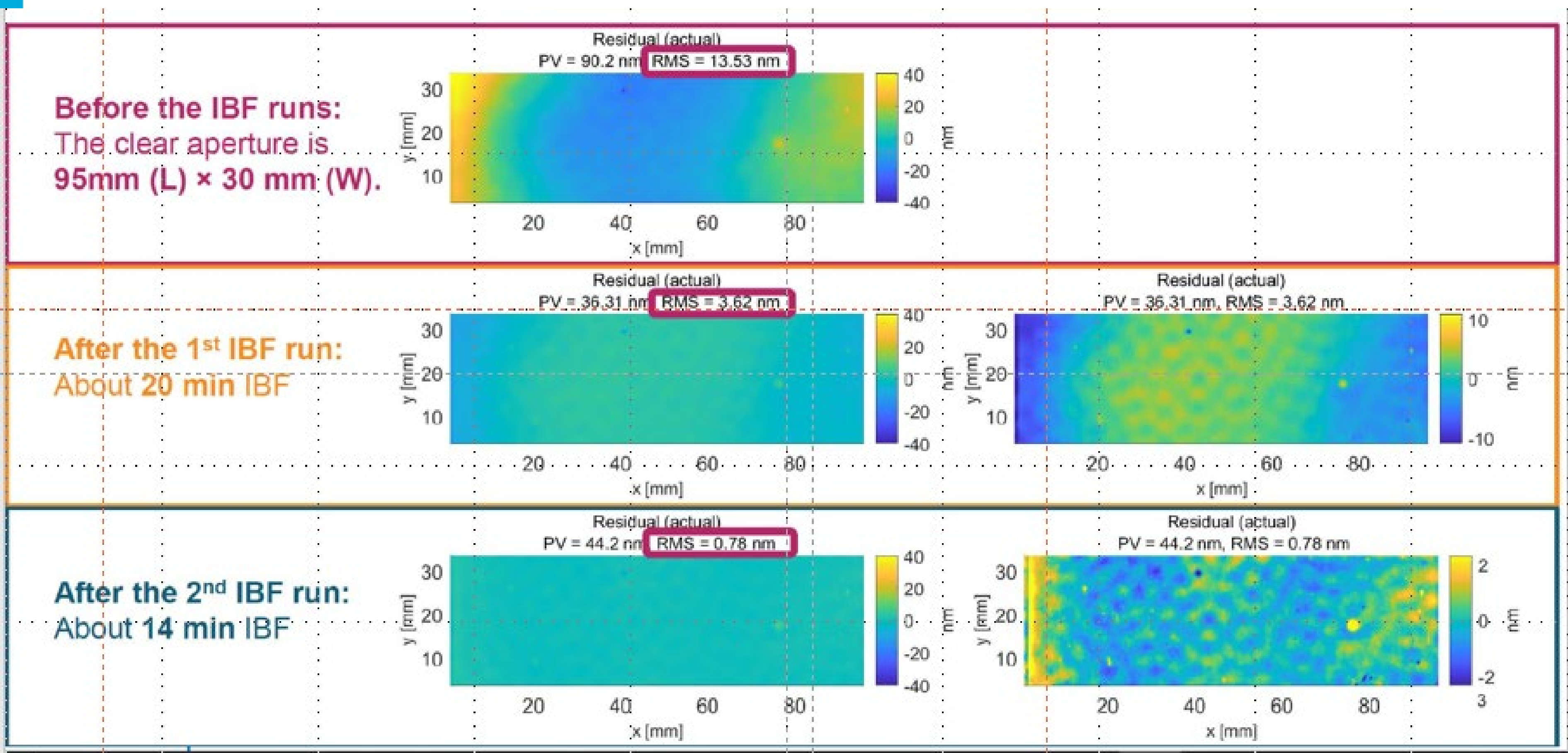
- To fix the non-planarity of the grating surface by IBF
- To investigate groove smoothing during the IBF, which i expected to be minimal



BERKELEY LAB | ADVANCED LIGHT SOURCE

Dmitriy Voronov 01/17/2023

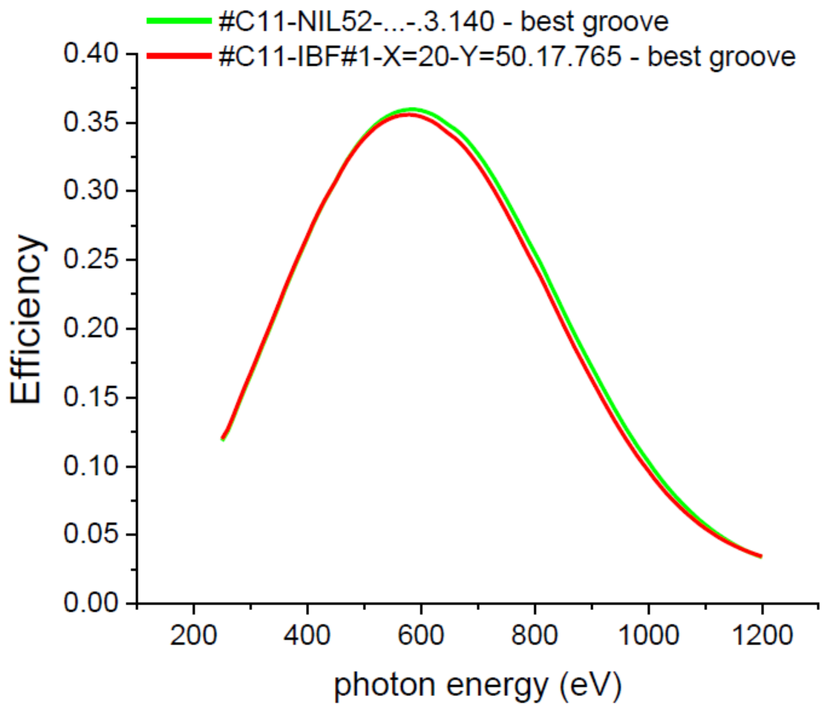
Example 2 FLAT Grating (ALS)

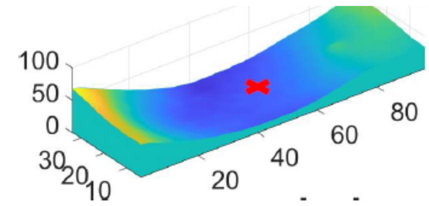


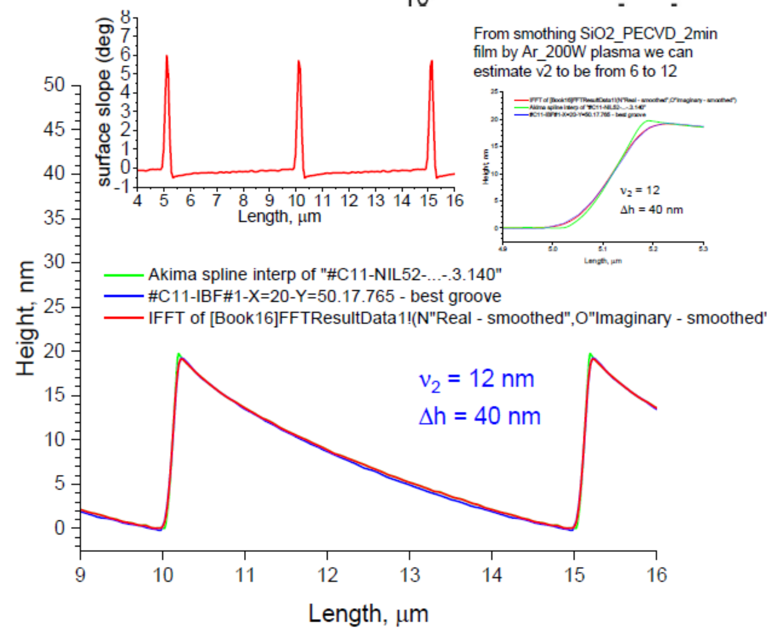
ADVANCED LIGHT SOURCE

Example 2 FLAT Grating (ALS)

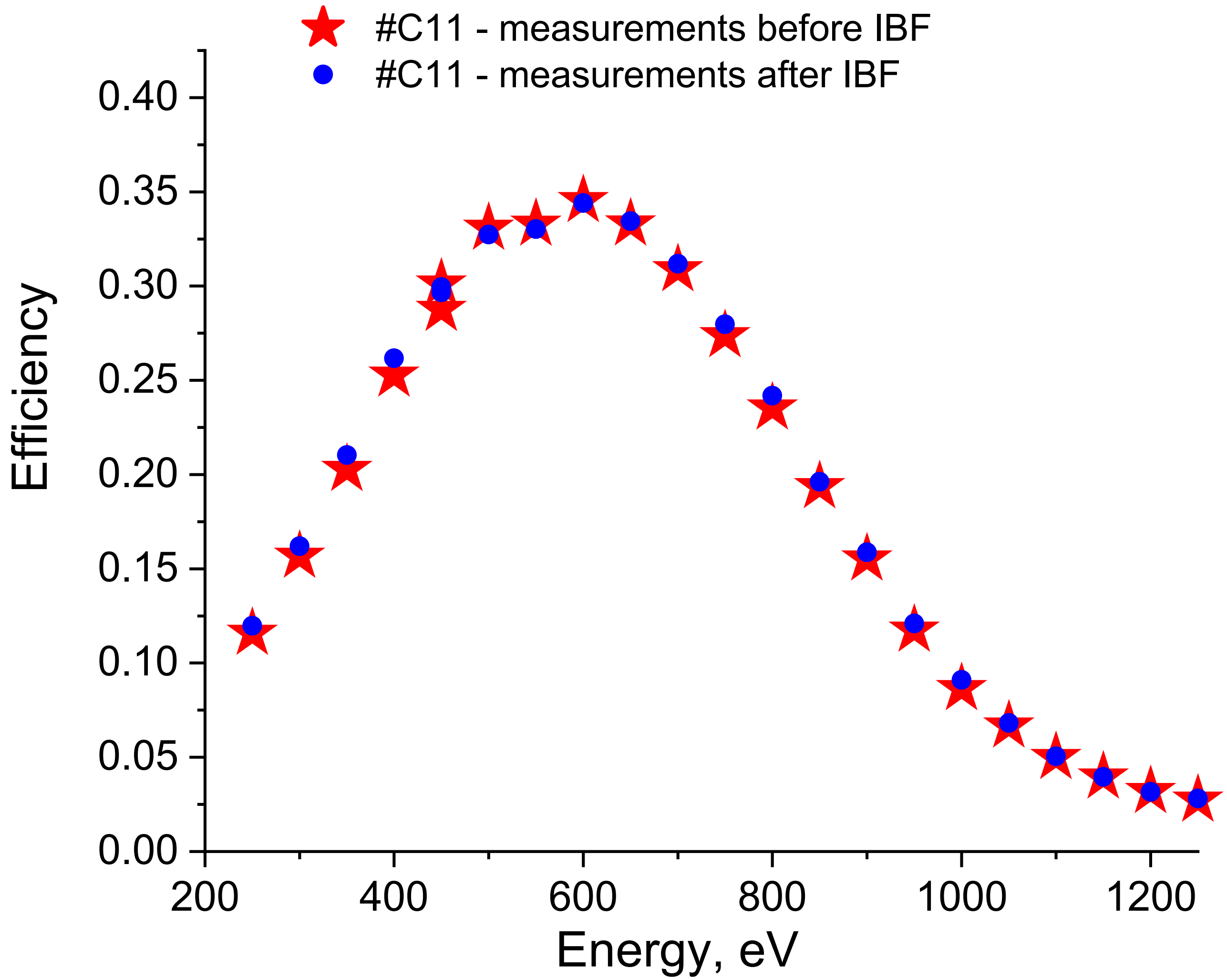
Efficiency simulations before and after IBF







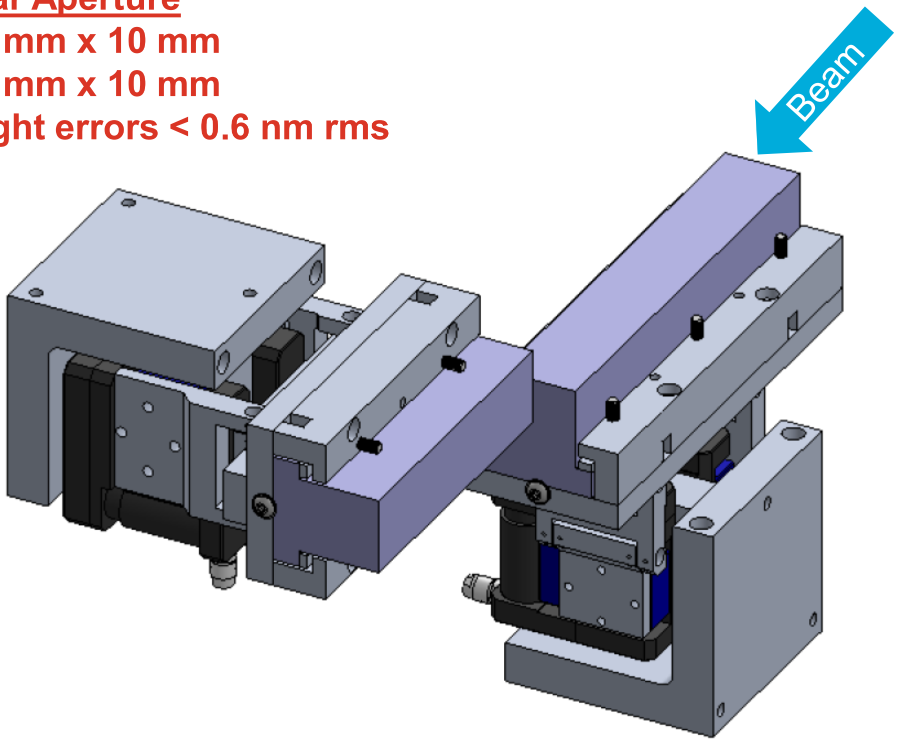
Example 2 FLAT Grating (ALS)



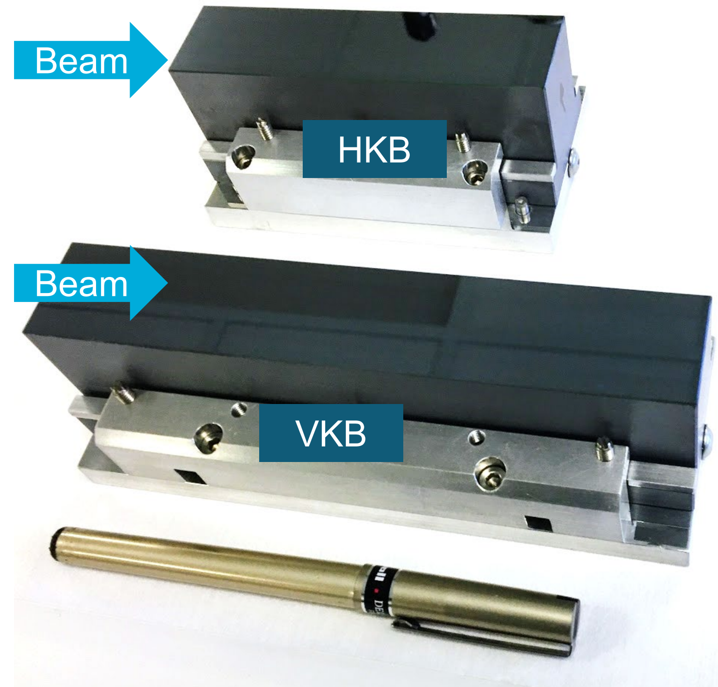
Example 3

APS/HPCAT Diffraction Limited KB System

Clear Aperture
100 mm x 10 mm
150 mm x 10 mm
Height errors < 0.6 nm rms



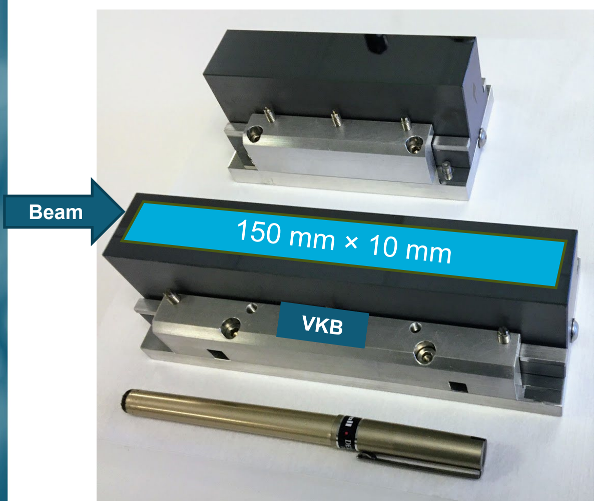
Mechanical designed by APS HPCAT Beamline



KB mirrors fabricated by NSLS-II

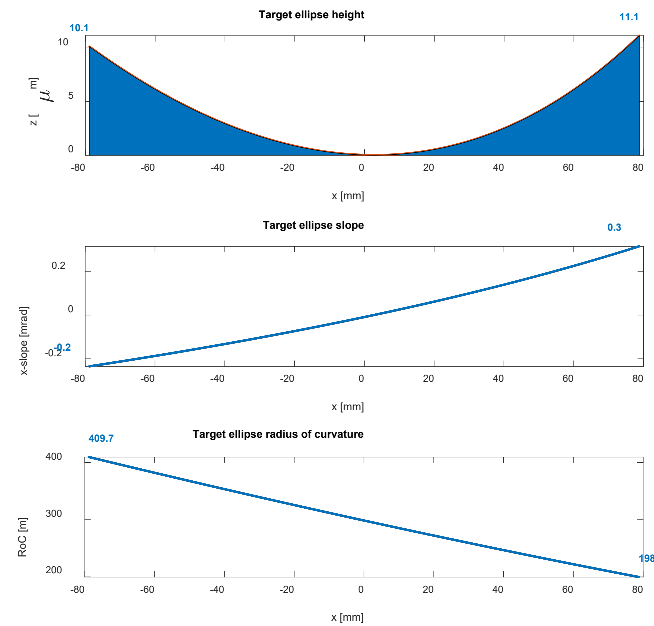
Example 3

HPCAT vertical KB mirror – specs



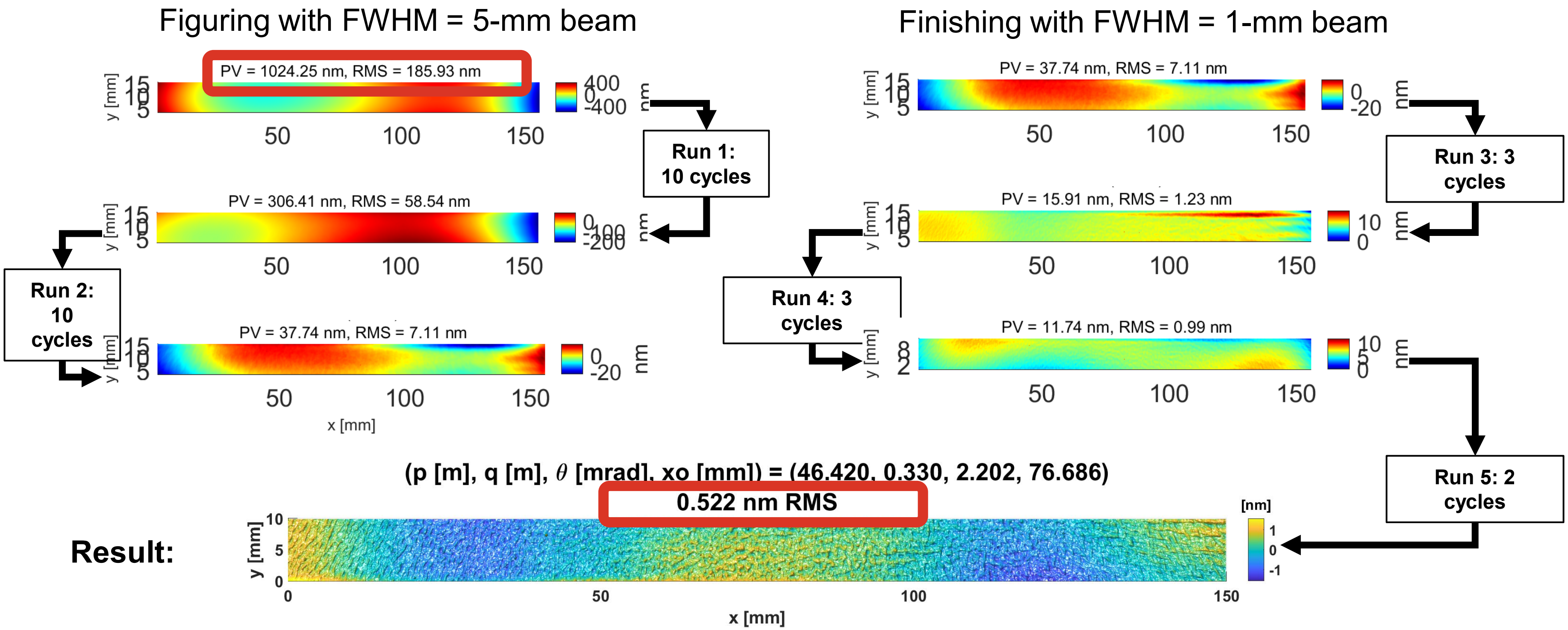
Base geometry: best-fit sphere

Shape	Elliptical cylinder, rectangular
Grazing angle, θ	2.2 mrad
Source-to-mirror-distance, p	46420 mm
Mirror-to-focus distance, q	330 mm
Length, L	160 mm
Width, W	28 mm
Thickness, T	40 mm
Active length, L_A	**$\geq$ 150 mm**
Active width, W_A	**$\geq$ 10 mm**
Height error RMS	**< 0.5 nm**
Slope error RMS	**< 0.1 μrad**
Roughness RMS	**< 0.2 nm**



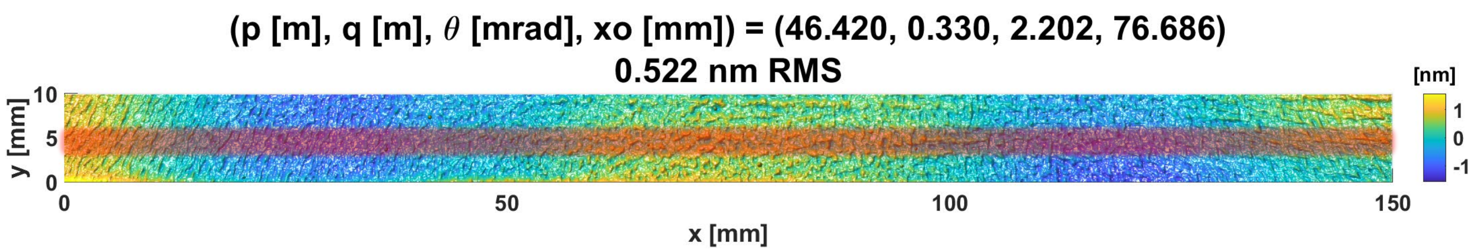
Example 3

HPCAT vertical KB mirror – figuring & finishing



Example 3

HPCAT vertical KB mirror – validation

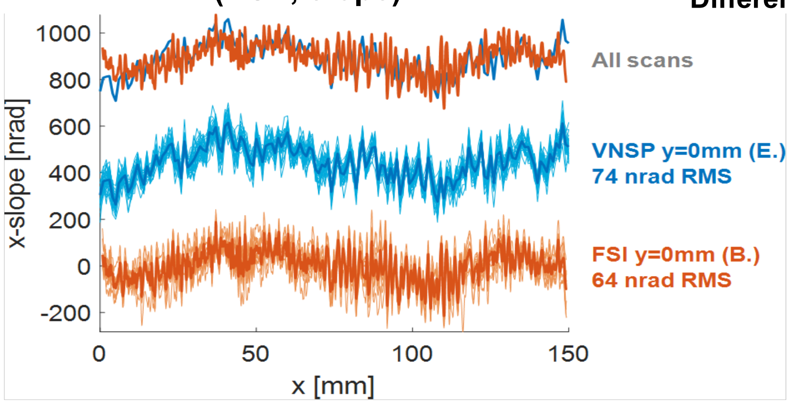


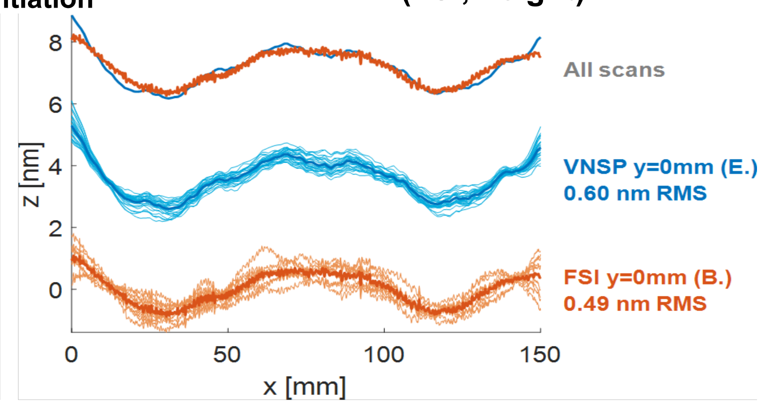
Nano-accuracy Surface Profiler (NSP, slope)

Integration

Differentiation

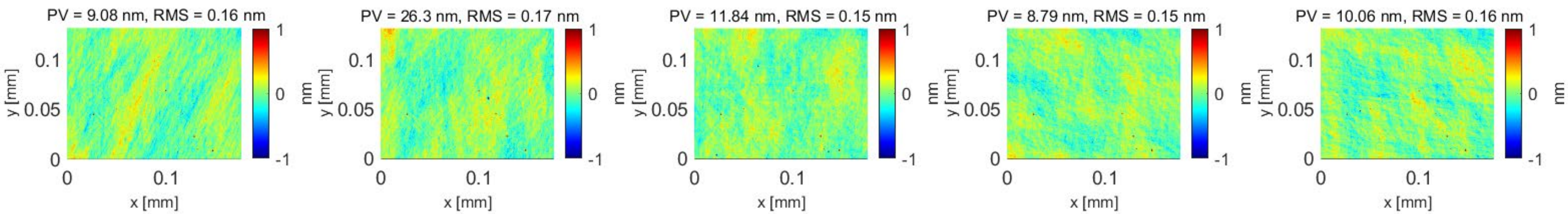
Fizeau Stitching Interferometry (FSI, height)



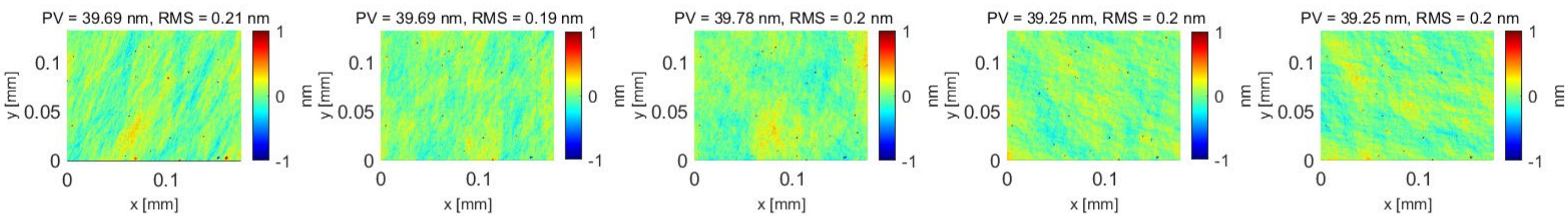


Example 3

Before ion beam figuring: 0.15 – 0.17 nm rms



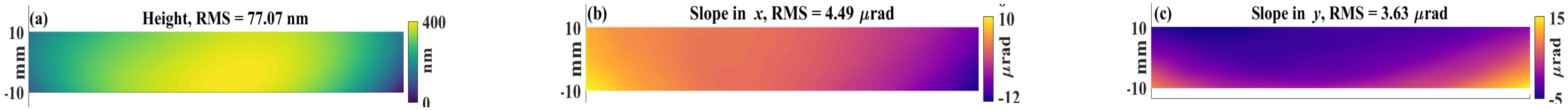
Roughness

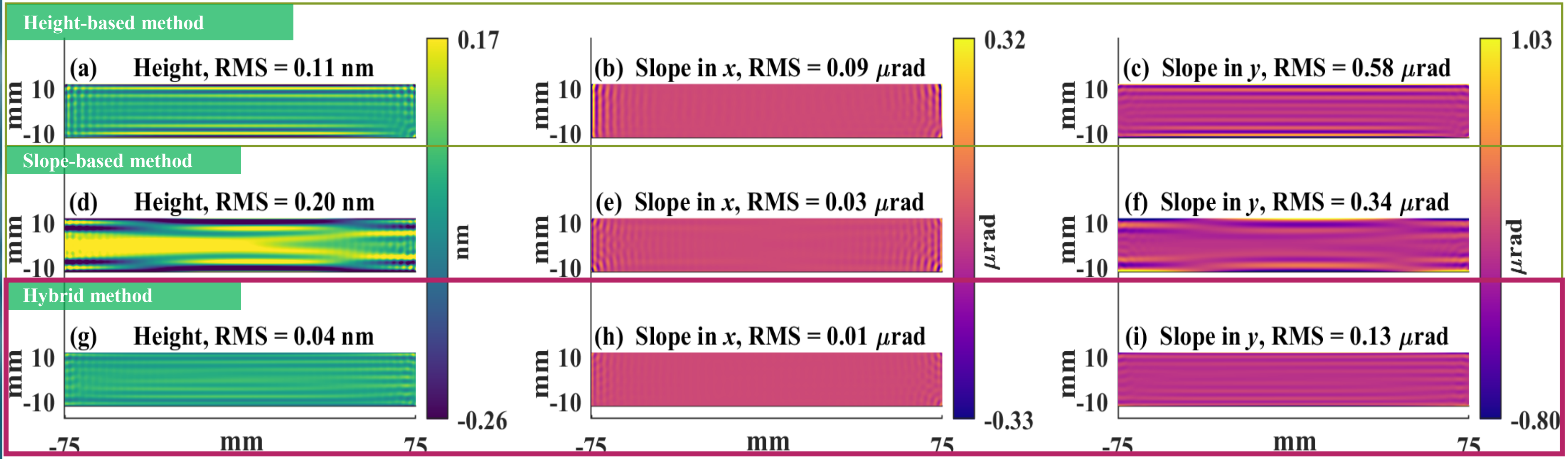


After ion beam figuring: 0.2 nm rms

Inverse: hybrid height-and-slope optimization

Initial height and slope errors

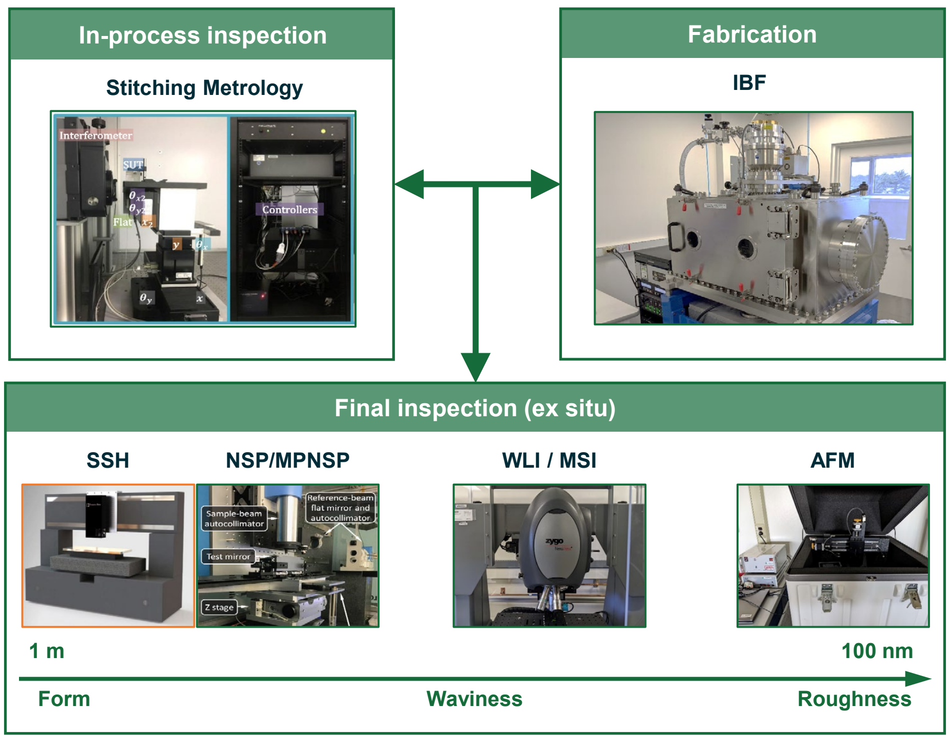


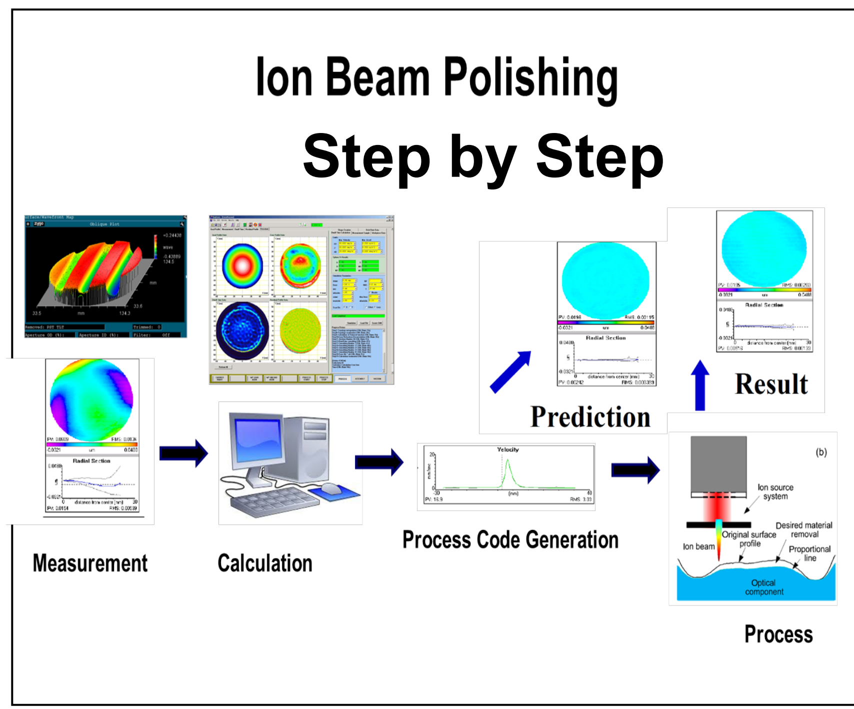


Hybrid method gives the smallest residual error estimations.

Conclusion

X-ray Diffraction Limited Mirror optical metrology and fabrication procedure is established at NSLS-II.





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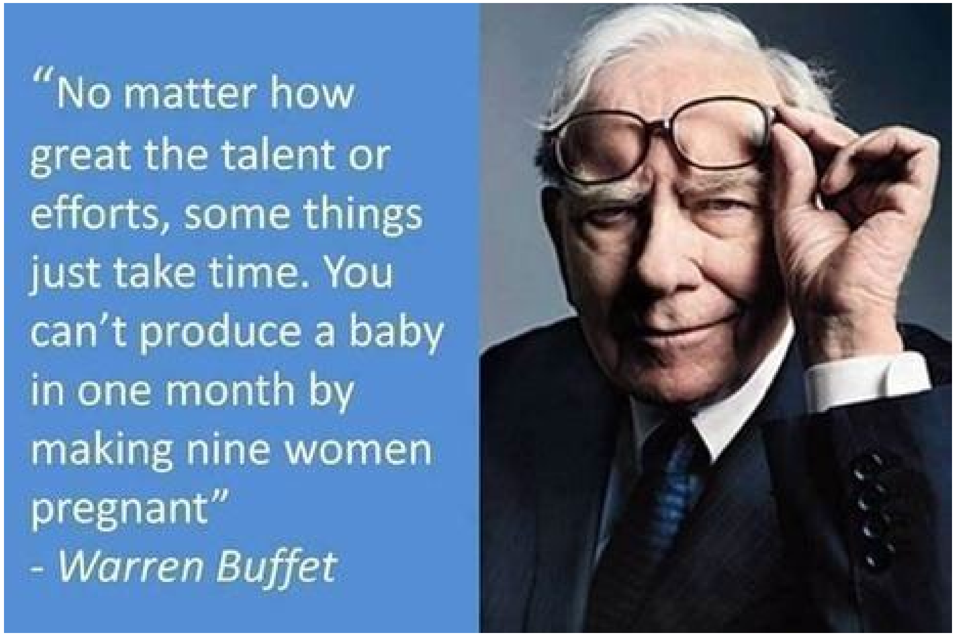
Thank you for your attention

Time is important and necessary



R&D is important and necessary