High Heat Load Optics

Developing a new generation of cryo-cooled mirrors for wavefront preservation

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BNL: Lei Huang, Tianyi Wang

ANL: Xianbo Shi, Jonathan Knopp

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Wavefront preservation is paramount for high coherent flux

• The advent of FELs, and source property upgrades for DLSRs with high coherent flux drives new and more challenging mirror specifications.
→ Coherence requires *height-based* surface specifications and high Strehl ratios.

• Requirements for stable, mid-power X-ray beams can be met with room temperature advanced cooling scheme like ***REAL***.

• However, higher power levels and potentially rapid, dynamic beam-profile changes motivate introducing steady mirror-cooling solutions without the need for dynamic compensation downstream: the ideal candidate is ***cryo-cooling***.

→ Implications on **cleanliness**, **stability**, **wavefront sensing**, **mirror mounting, metrology**

Cryo has been used for many years on crystals
At the level we need now, we are in uncharted territory.

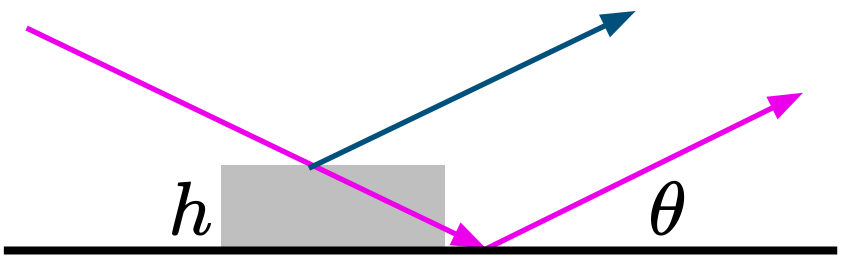
We need a multi-lab, shared effort to develop and implement cryo-cooling, giving US light sources a competitive advantage.

We have been engaged in a **collaborative** and **successful** multi-lab R&D project.
We need to do the same for cryo-cooling optics and the related technologies

Wavefront preservation demands sub-nm surface specifications

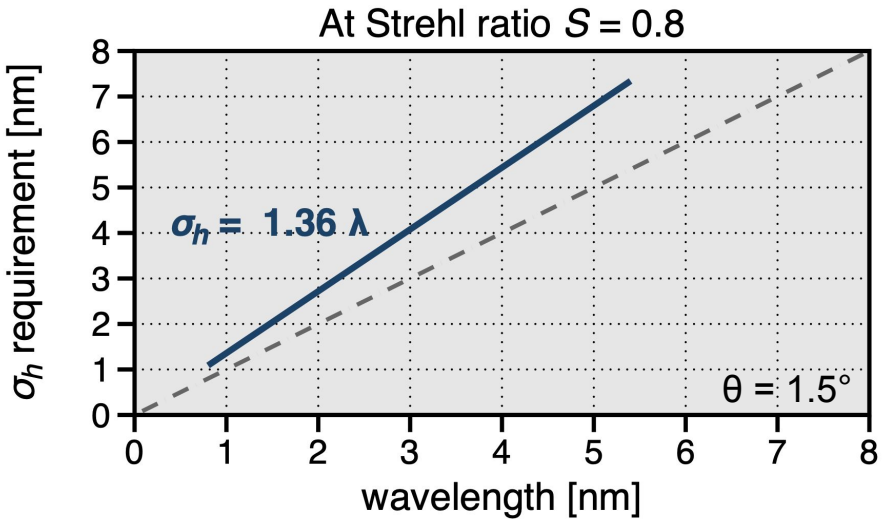
path length change

$$\Delta s = 2h \sin\theta$$



Requirements from a Strehl ratio, S

$$\sigma_h \leq \frac{\lambda_n \sqrt{1-S}}{4\pi \sin\theta}$$



Mirror surface quality requirements are on the **sub-nm** level, set to satisfy shortest wavelength.

We separate the **dynamic** thermal deformations from the static optical shape specifications.

Wavefront preservation demands sub-nm surface specifications

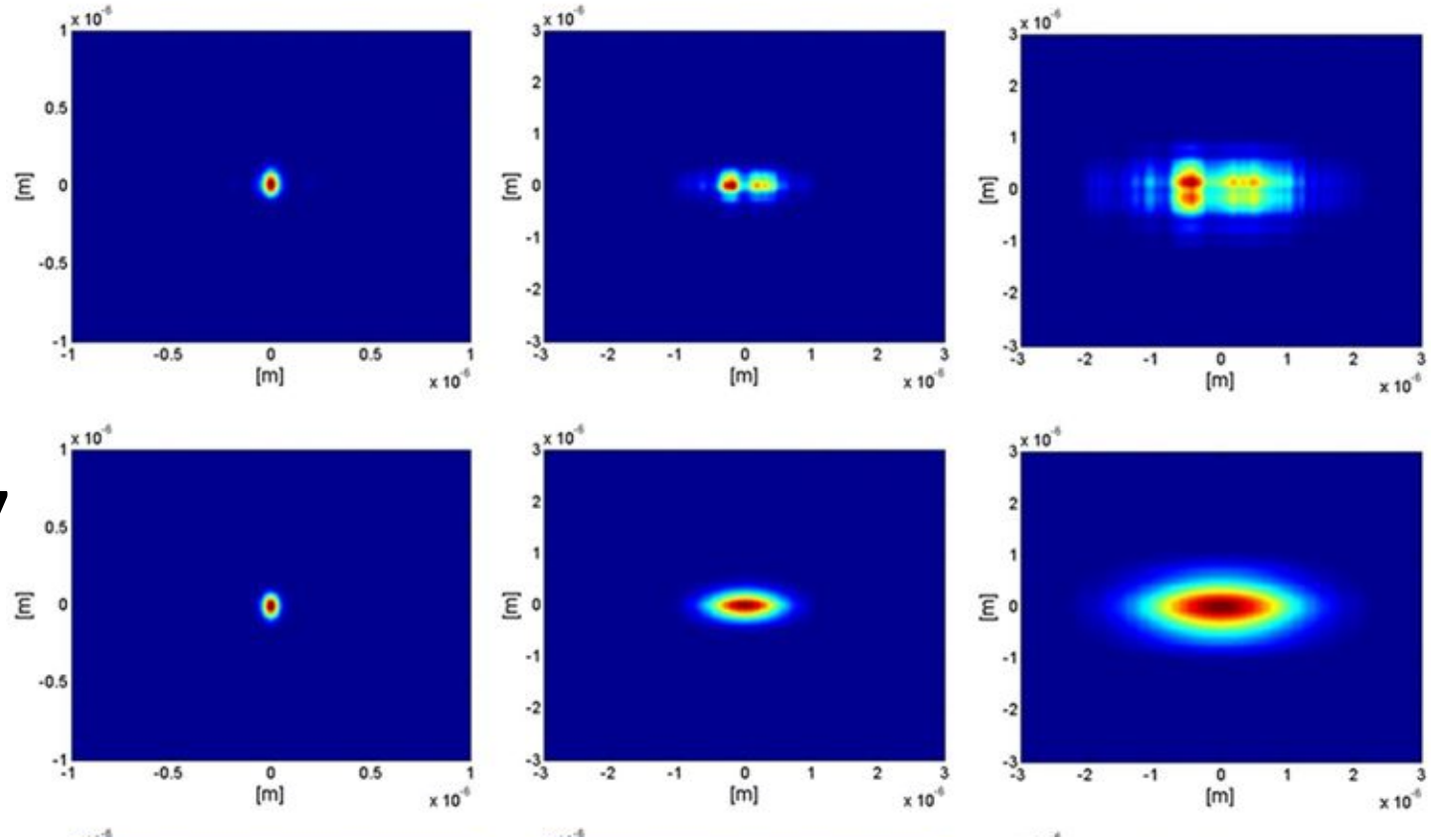
A SR of 0.8 is not enough
for measurements out of focus.

Requirements from a Strehl ratio, S

$$\sigma_h \leq \frac{\lambda_n \sqrt{1-S}}{4\pi \sin\theta}$$

SR≈0.8

SR≈0.97



Examples for a SR=0.97 (LCLS specs):

HXR: 1.35 mrad, 13 keV → **0.56 nm rms**

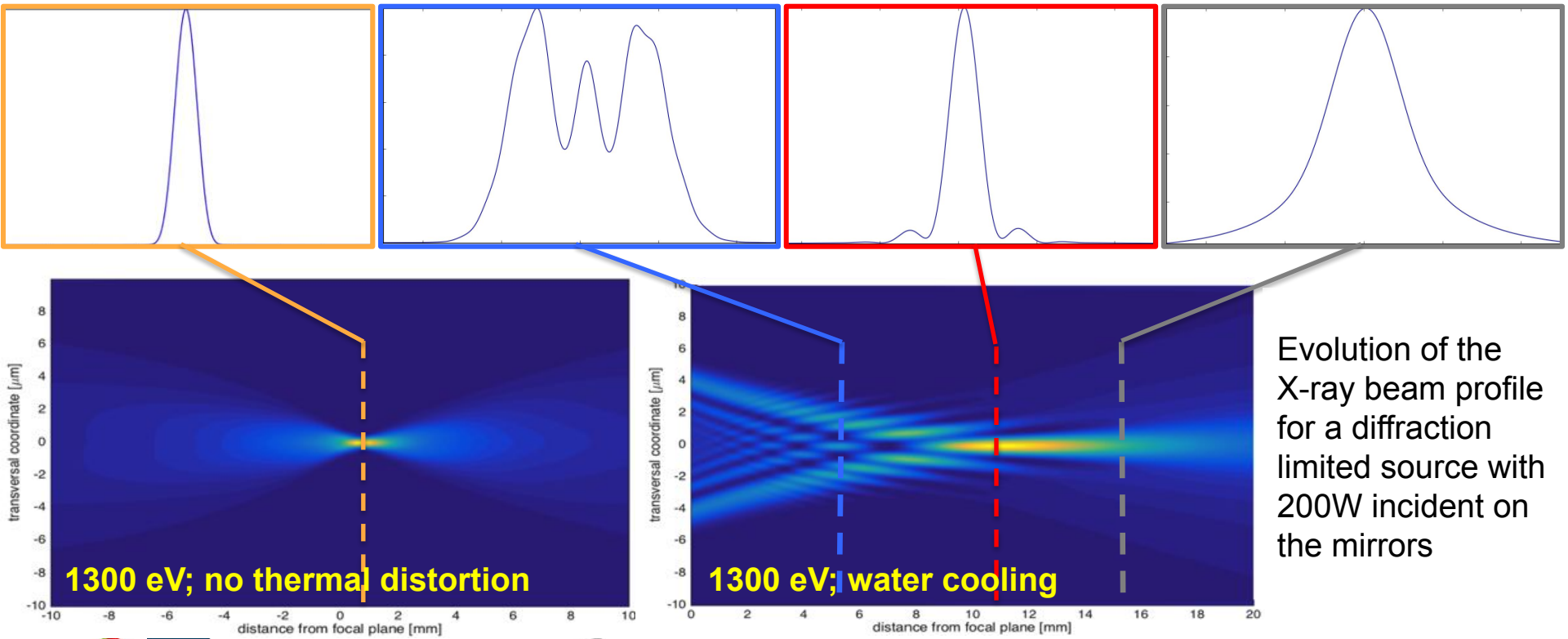
SXR: 12.0 mrad, 1.3 keV → **0.63 nm rms**

(after 3 mirrors)

Wavefront preservation—factors to consider

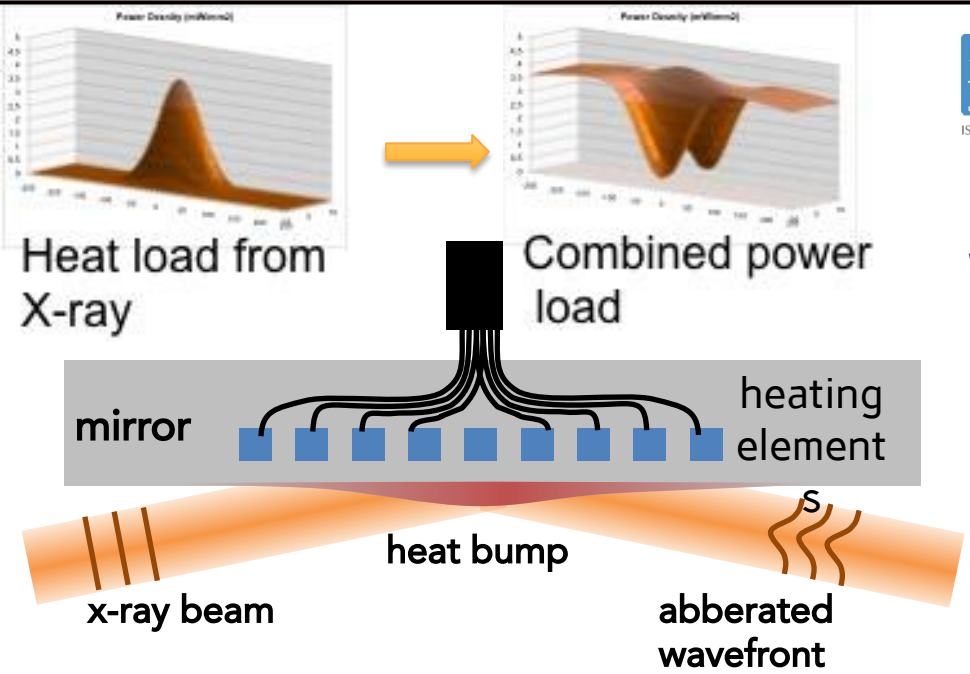
- Stress-free mirror holders
- Sub-nm polished mirrors (with limited high spatial frequency errors)
- Removal/compensation of aberration and defocusing (usually through active optics or perfect alignment)
- Remove or limit the thermally-induced deformation (with optimized cooling scheme or adaptive optics)

The thermal deformation has a “clear” effect on the wavefront (in and out of focus)
This is, of course, bad… but can be used to test the mirror (see next talk)



Evolution of the X-ray beam profile for a diffraction limited source with 200W incident on the mirrors

SLAC: *REAL* Mirror: room-temp. shape stabilization



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Optimizing X-ray mirror thermal performance using matched profile cooling

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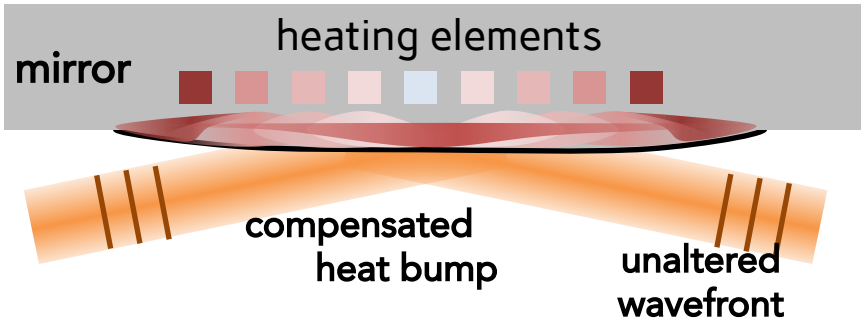
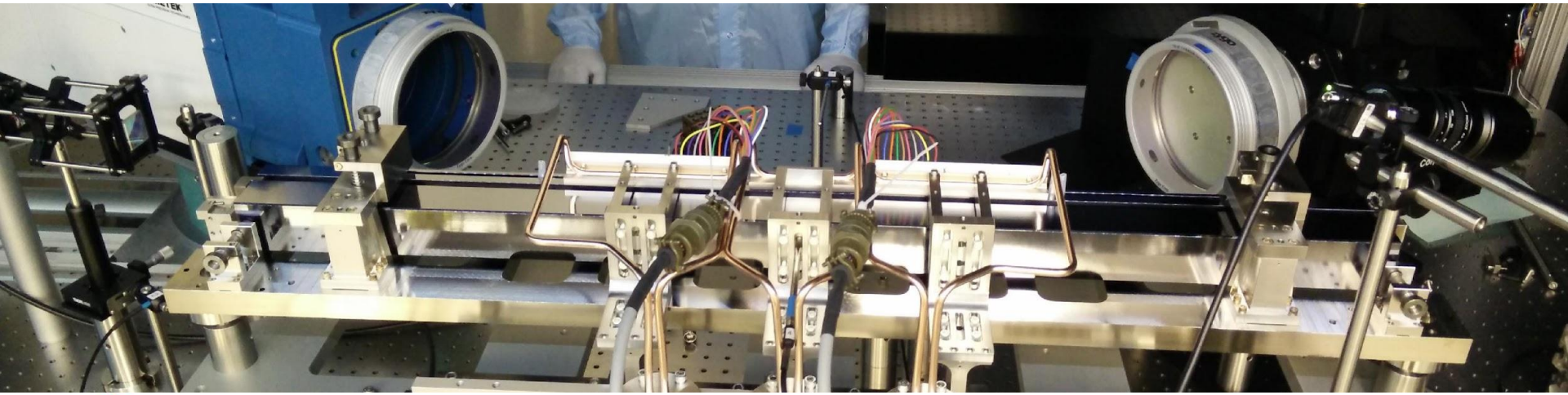
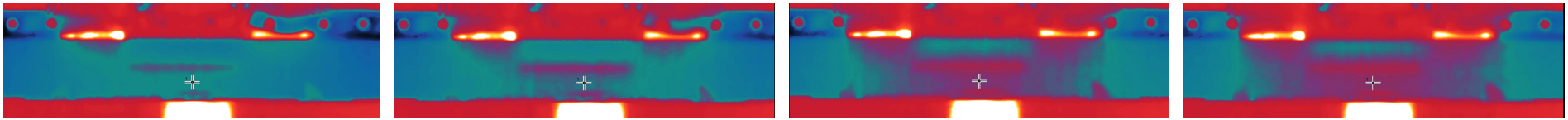
Wavefront Preserving Mirror project was supported by DOE BES ADRP (Lessner): **SLAC / LBNL / ANL / BNL**





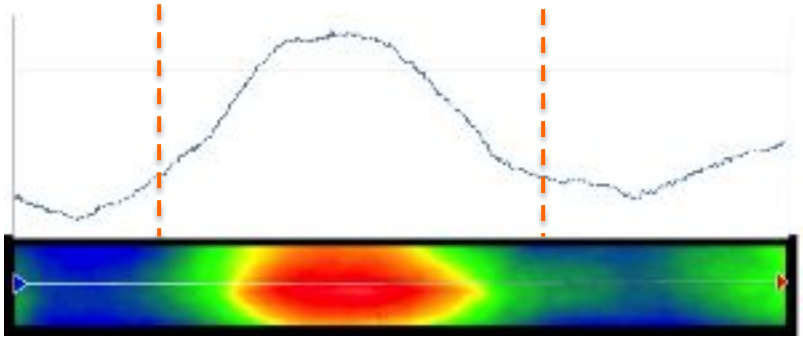
SLAC: *REAL* Mirror, ex situ demonstration



1st demonstration of X-ray mirror shaping (correction) using heaters

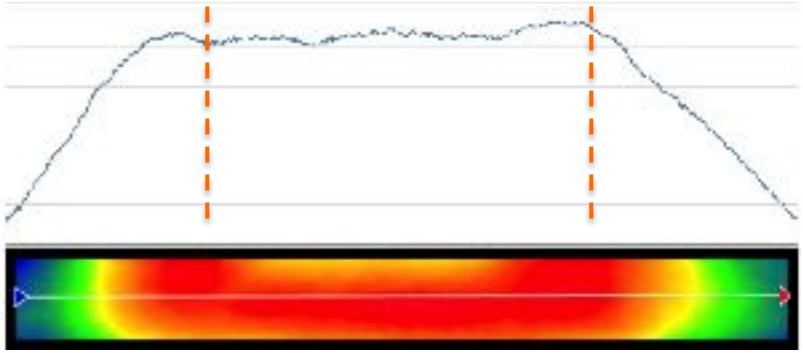
$\Delta T < 2^{o}$ for 15 W absorbed

12.7 nm rms before REAL

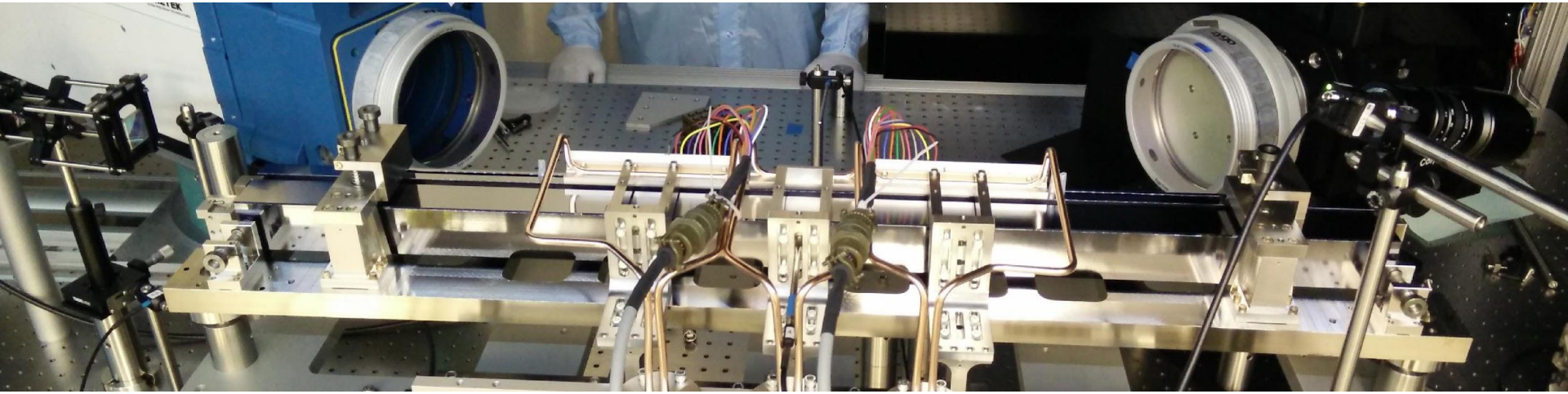


Heat Load induced by an IR laser (15W)

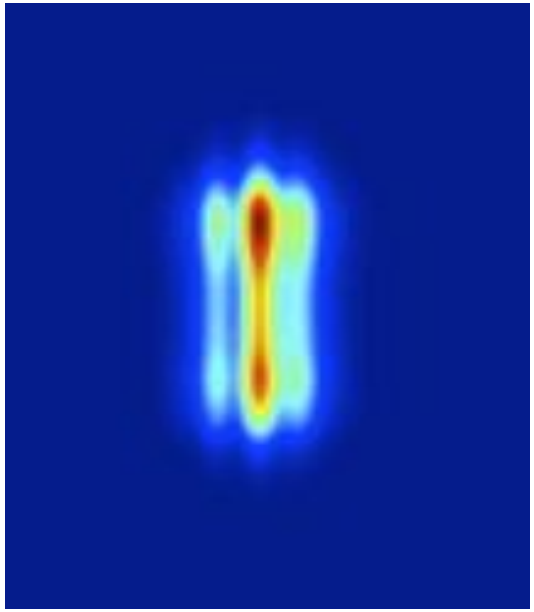
1.1 nm rms after correction



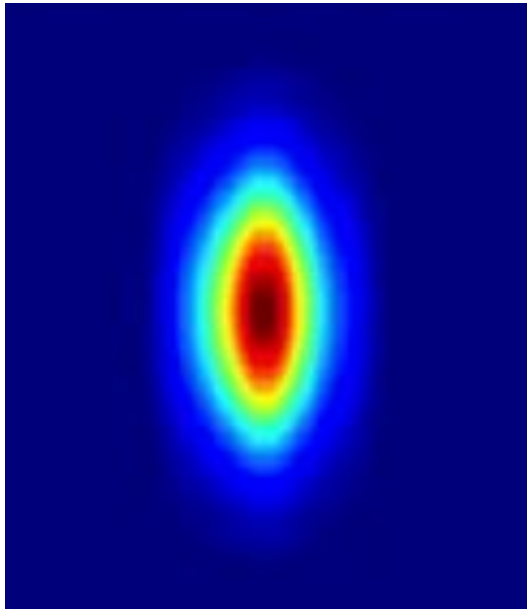
Combined effect (REAL + heat Load)



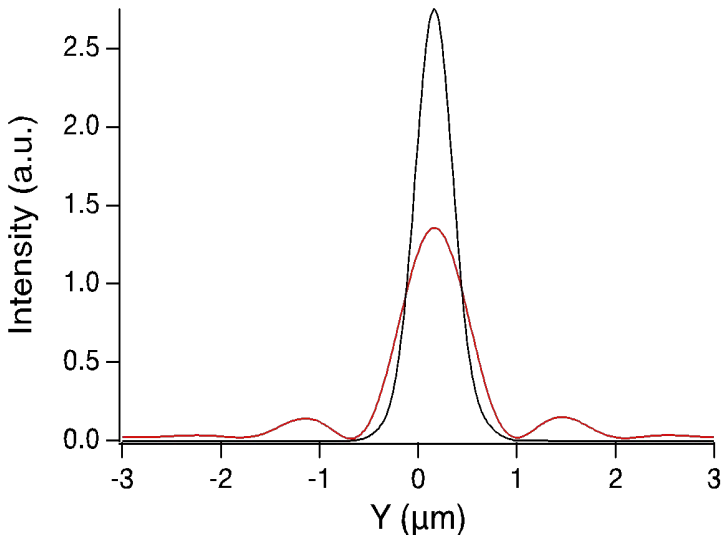
SLAC: *REAL* Mirror, potential improvement



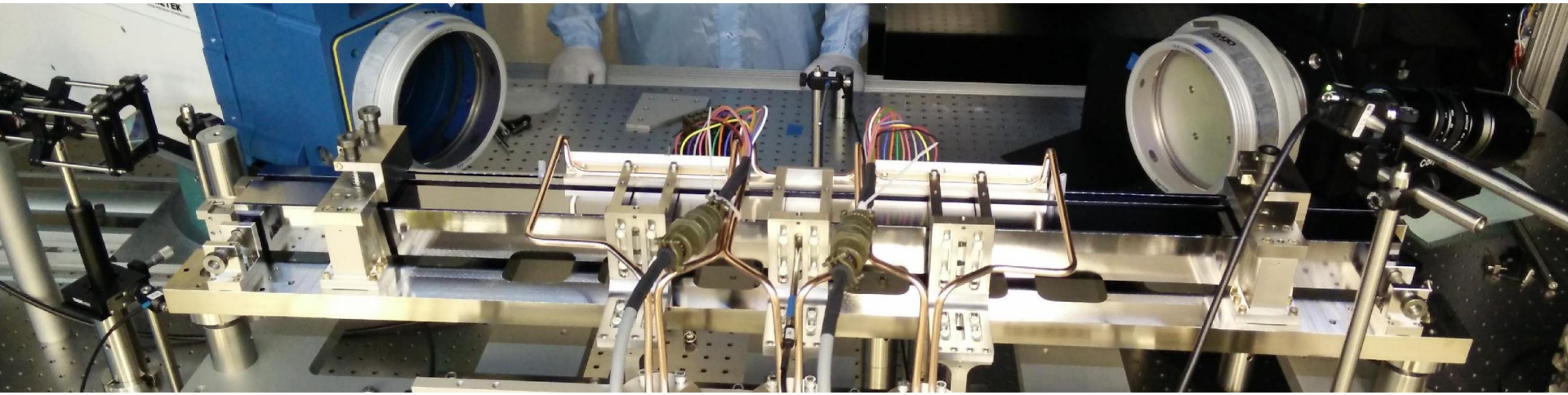
Without correction



Predicted, after correction



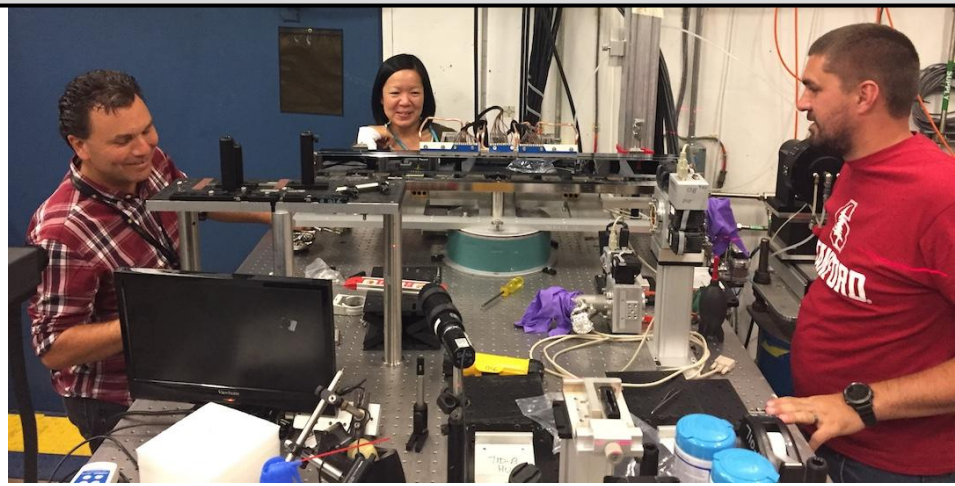
We predicted 2x fluence gain, in focus

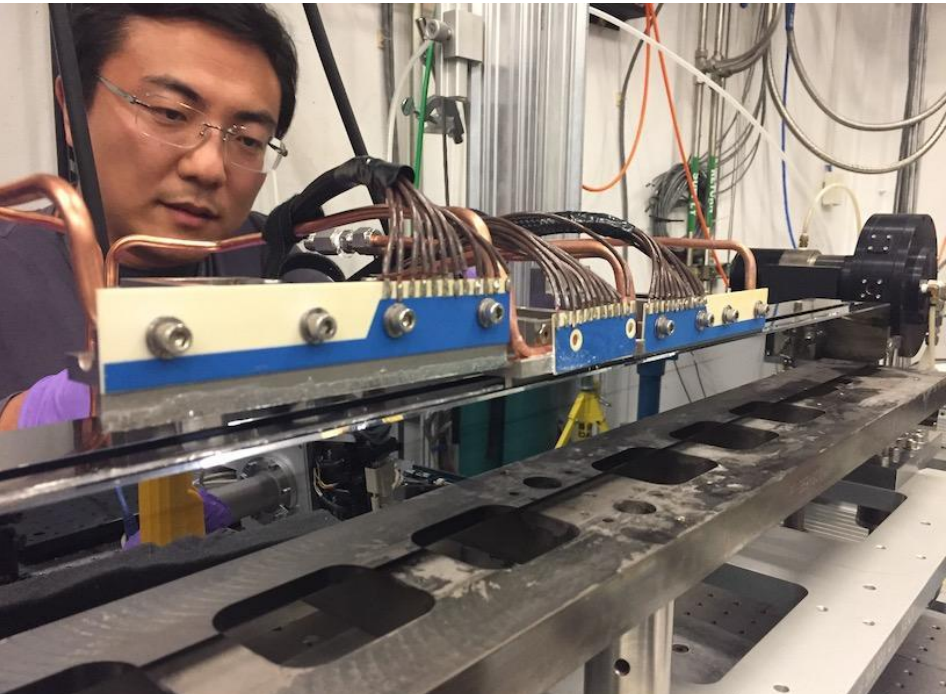


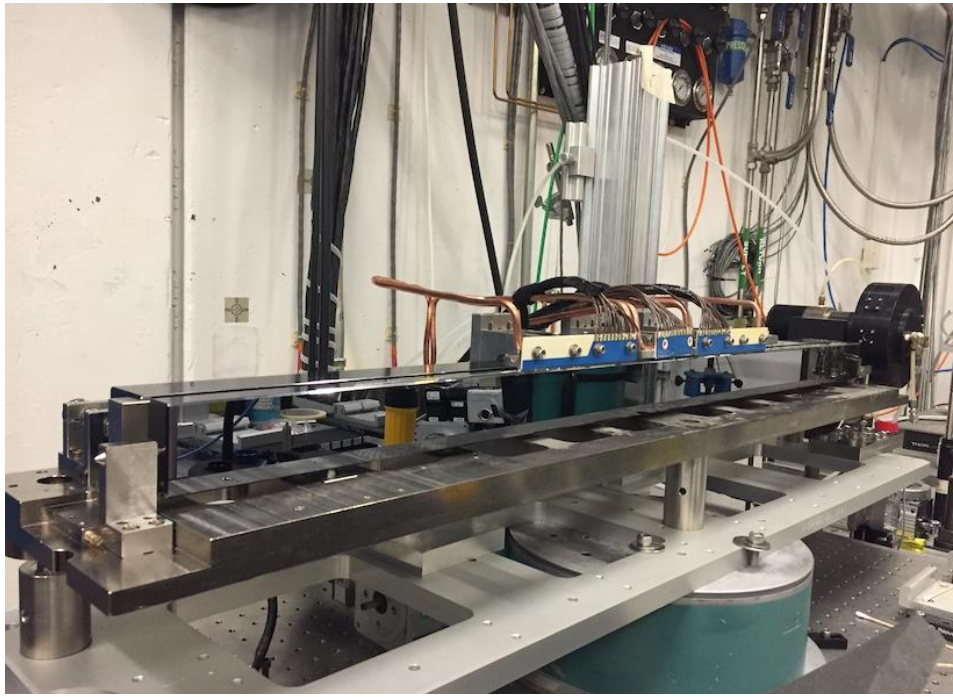
REAL Mirror: Tests @ APS ID7

The 1-m-long mirror and the REAL heaters were tested at-wavelength at APS.

Discussion in the next talk.

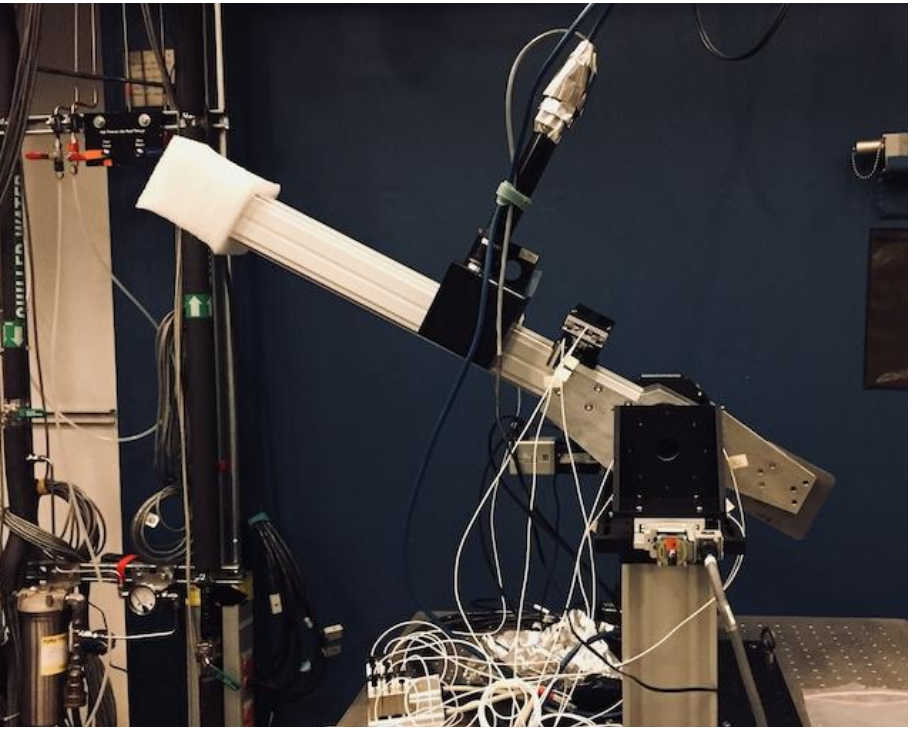




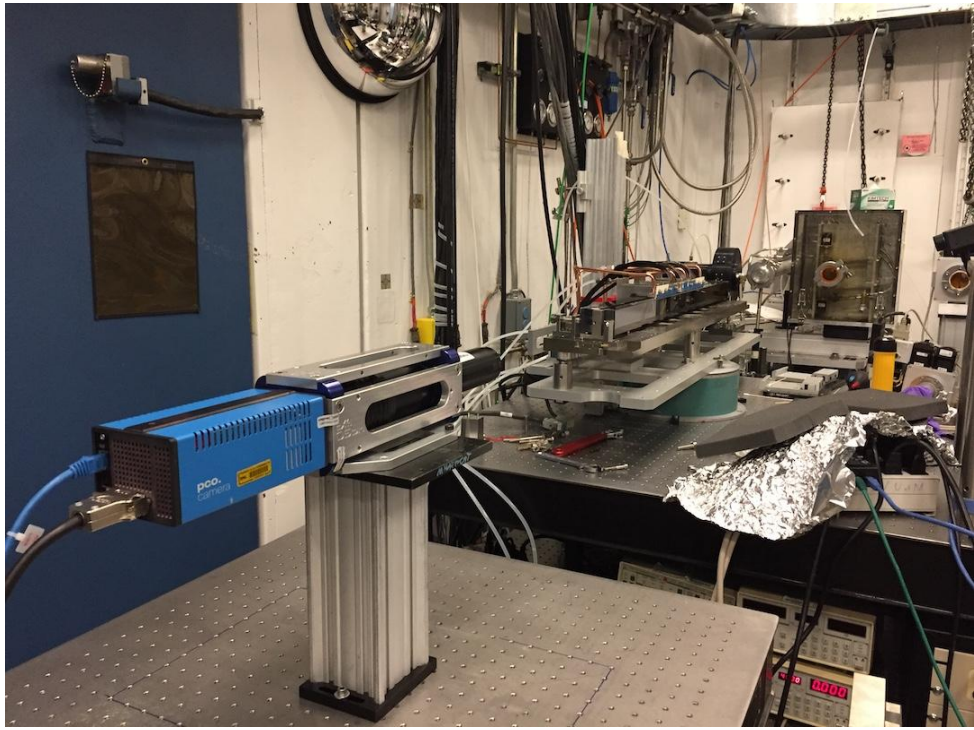


REAL Mirror: Tests @ APS ID7

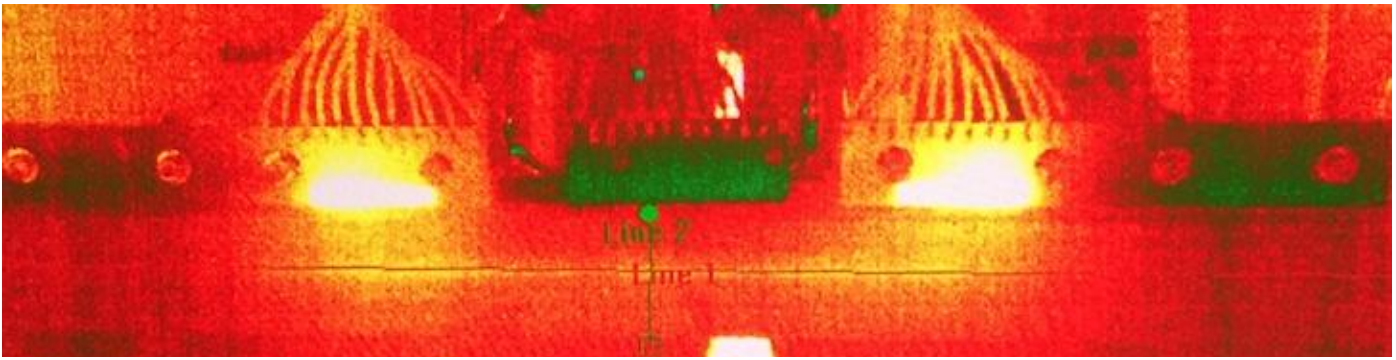
Shearing (Talbot) interferometer



Hartmann wavefront sensor



imagine optic



Shearing (APS)
S. Kearney, L. Assoufid, *et al.*
Conference: C18-06-25.9, p.THPH27

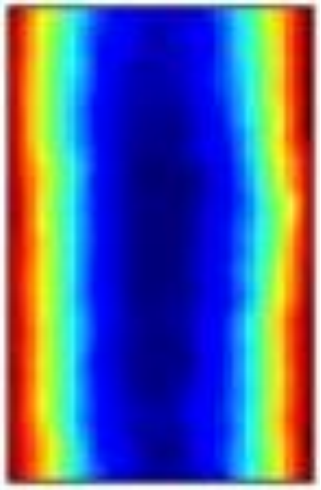
Hartmann (Imagine Optics, BNL)
G. Dovillaire, O. de La Rochefoucauld, with M. Idir, L. Huang

REAL Mirror: room-temp shape stabilization

Example of one correction with ≈ 10 W absorbed by the mirror over ≈ 200 mm

Residual 115 pm RMS
389 pm P-V

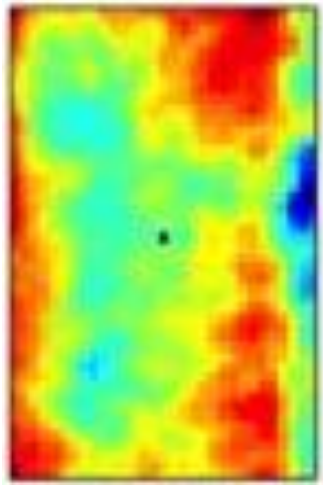
Thermal Bump



Like a **40 nm P-V** thermal bump

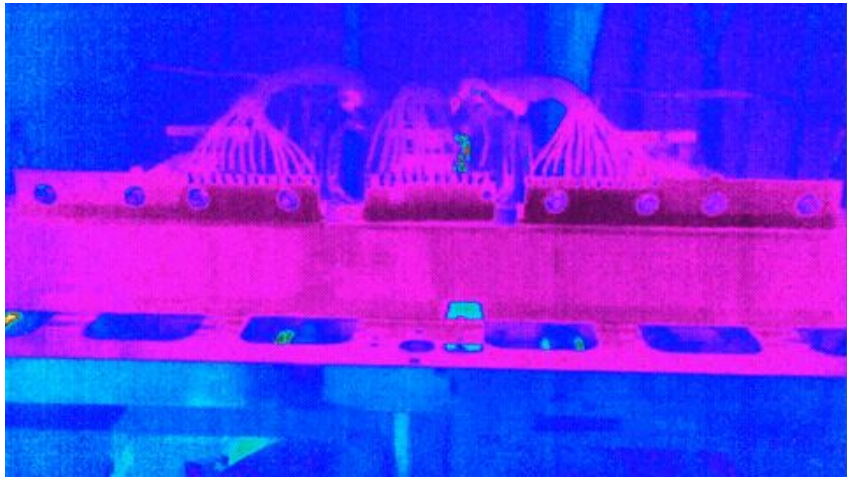
Residual 15 pm RMS
112 pm P-V

After correction (from calculation)



Down to **1.5 nm rms** after correction. (Noise limited.)

thermal image

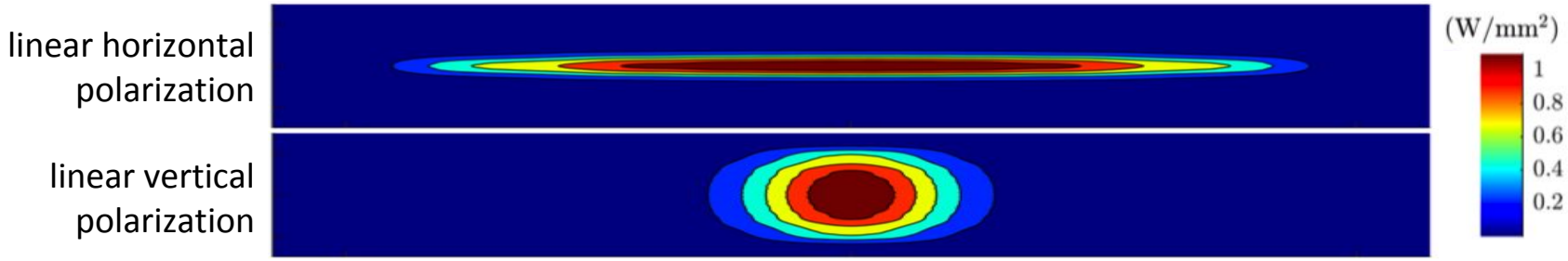


λ beam = 0.08 nm

- Proven to be effective for low- (maybe mid-) power density.
- Perfectly tailored for LCLS where the expected power absorbed by the mirrors will not exceed 20 W (when a Strehl Ratio > 0.9 is required).
- Optimization is thermal and relatively slow. Not suitable for dynamic compensation.

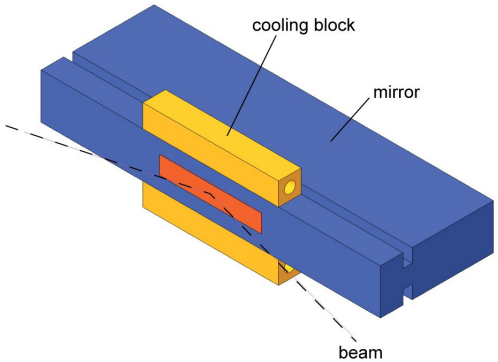
ALS-U: Conditions demand cutting-edge mirrors

The EPU beam footprint changes rapidly and dramatically

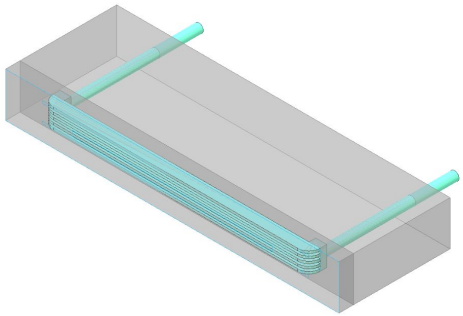


Cryo Si has remarkable properties: *high thermal conductivity and zero CTE at 125 K.*

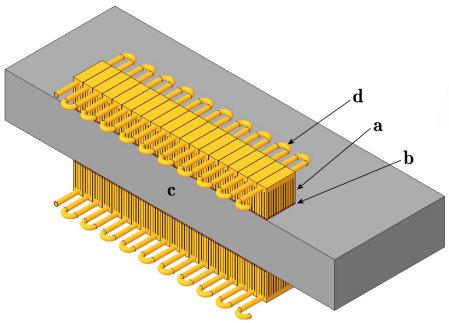
- With extensive FEA modeling, ALS-U studied *Room Temperature* and *Cryogenic* solutions.
- Active engagement with leading groups and experts worldwide.



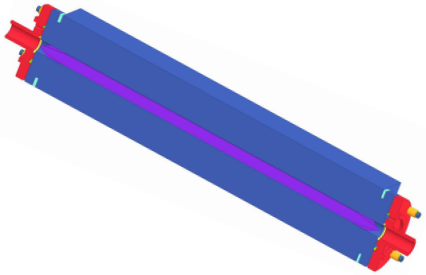
water and cryo
side cooling



water
internal cooling



cryo
side cooling

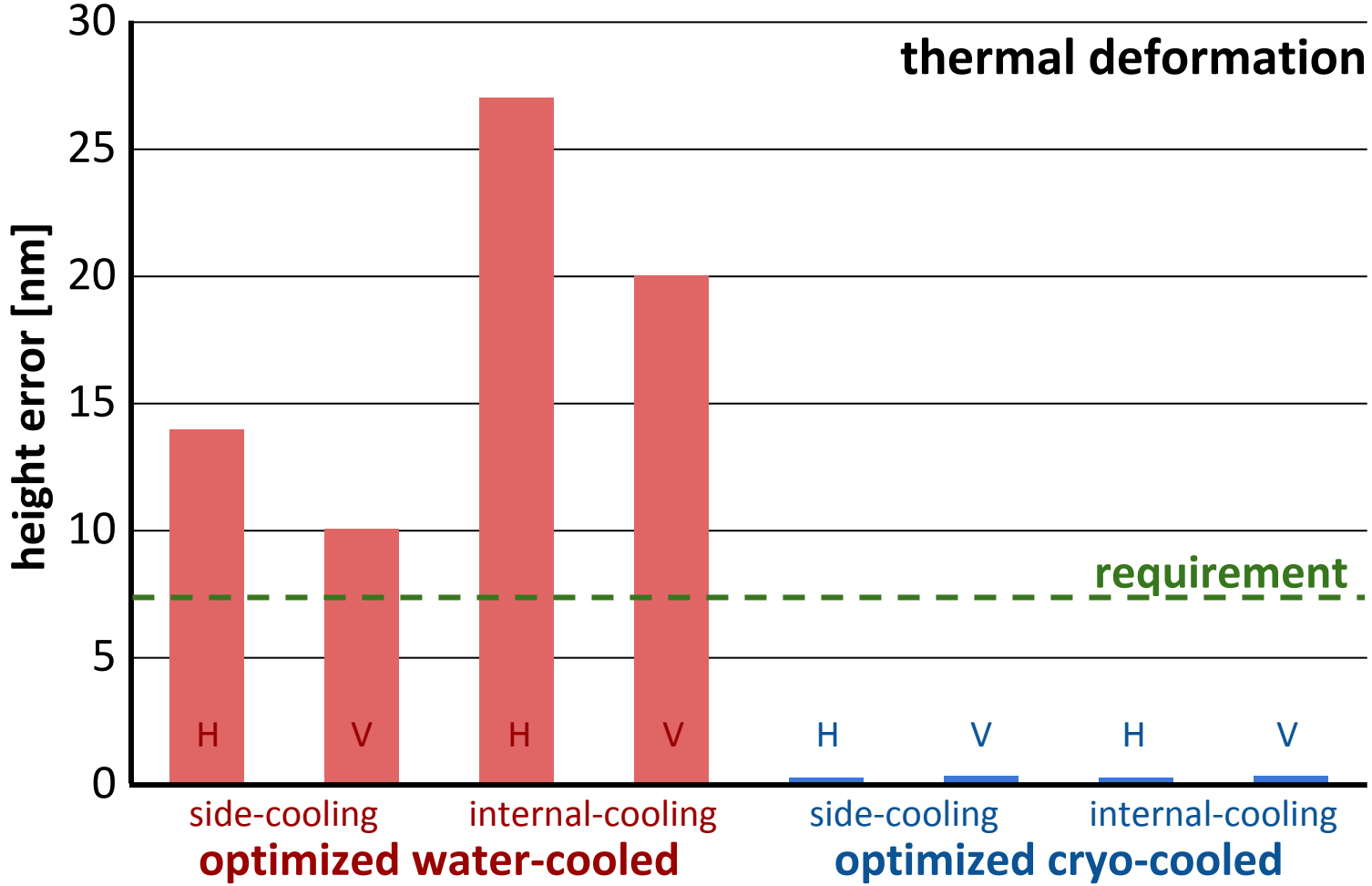


cryo
internal cooling

Credit: Grant Cutler, Howard Padmore

ALS-U project has selected cryo-cooled M1s

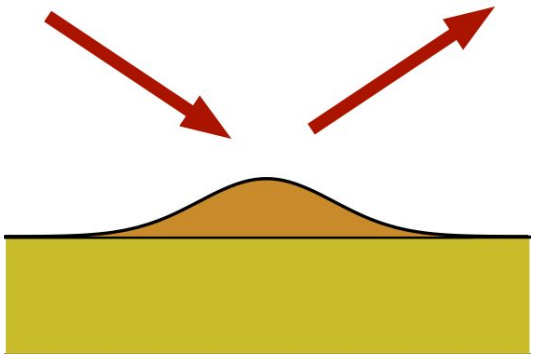
LN2 cryo solutions meet the height error requirement without *dynamic adaptive correction* or *narrowly engineered corrections for limited cases*



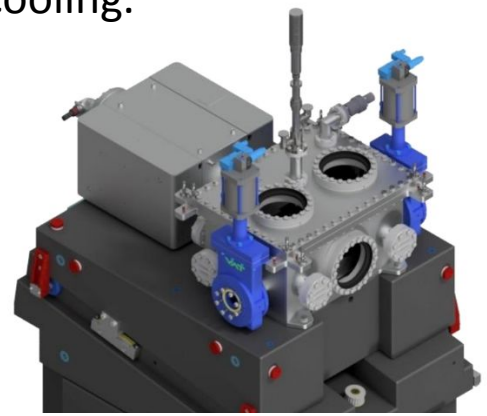
Credit: Grant Cutler, Howard Padmore

Impact of cryo-cooling on essential, related technologies

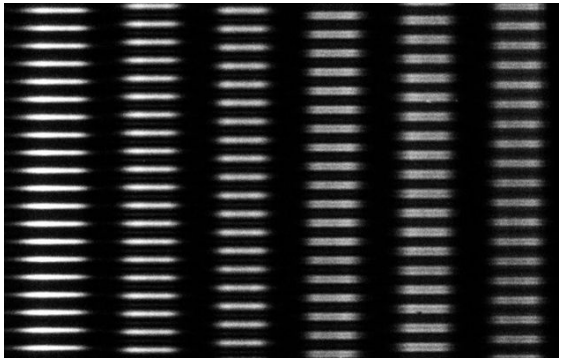
Carbon Mitigation
Working at cryo-temperatures raises concerns about carbon and cleaning.



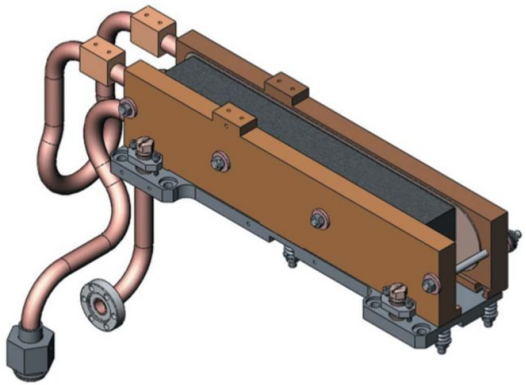
Stability
Coolant flow rates are much lower for cryo-cooling.



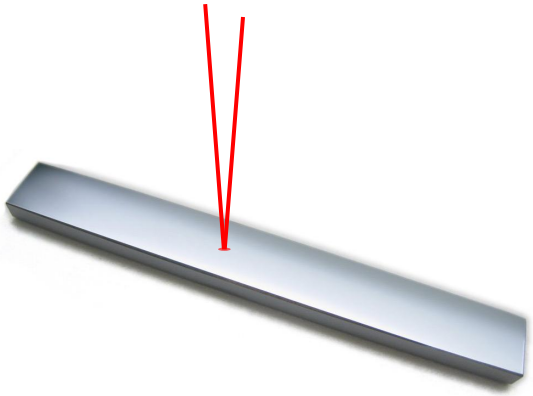
Wavefront Sensors
Achieving and maintaining fine alignment requires *feedback*.



Mechanical deformations
Preserve the mirror profile while cooling down, RT to LN



Metrology
Measurement at cryo temp. is essential for development.



Cryo-cooling: Implications

With more high-coherent flux beamlines constructed or planned, we believe that more facilities will be choosing cryo-cooling.

We need a collaborative program for development and prototyping

Selection of

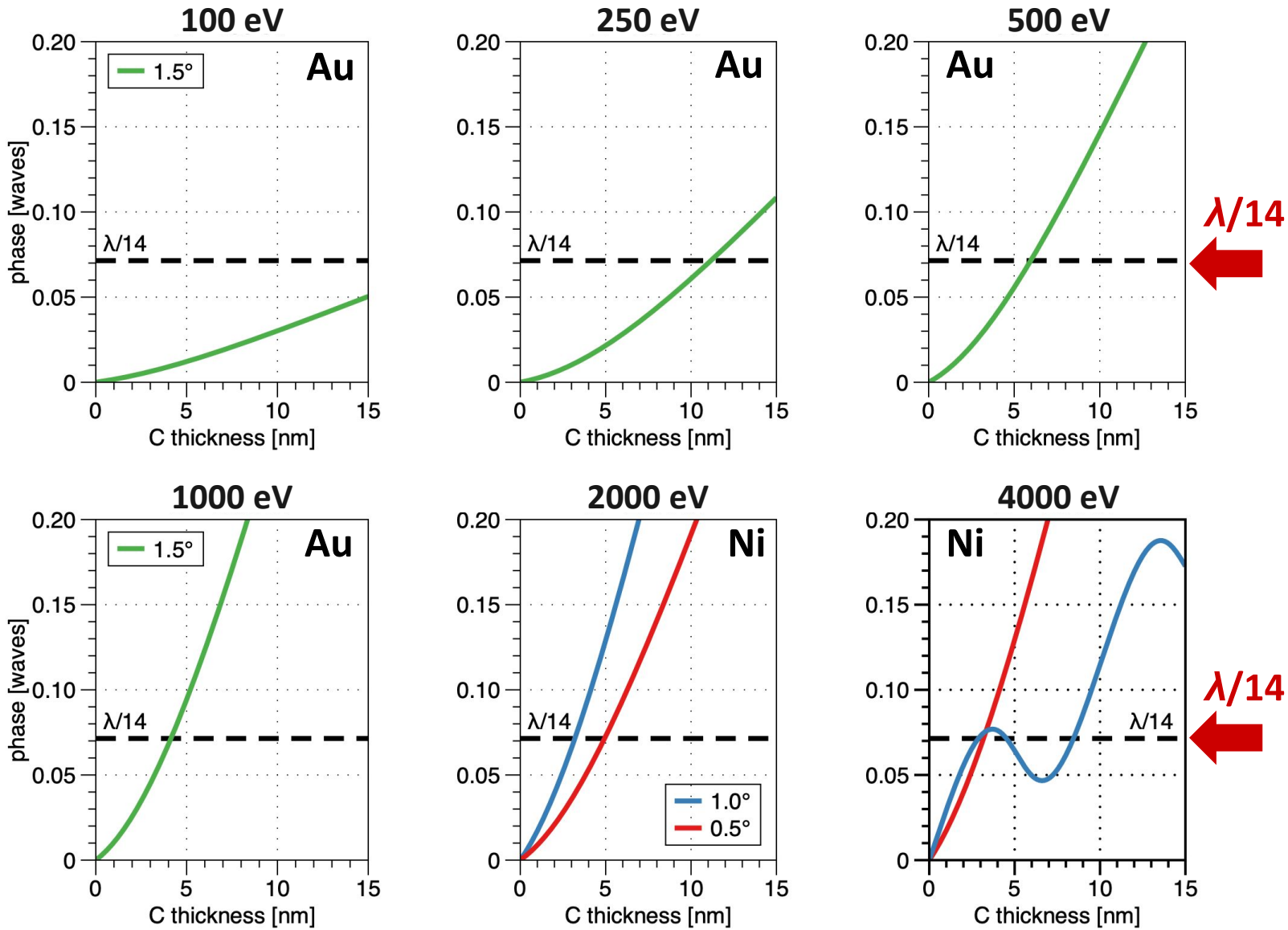
- Cooling mode: internal vs. side, mirror geometry, etc.
- Coolant: LN2 or Ar
- Coolant pumping
- Interface standards
- Carbon contamination mitigation

Mechanical stress and deformation with thermal cycling is a major concern

Development requires Infrastructure for metrology at cryo temperatures

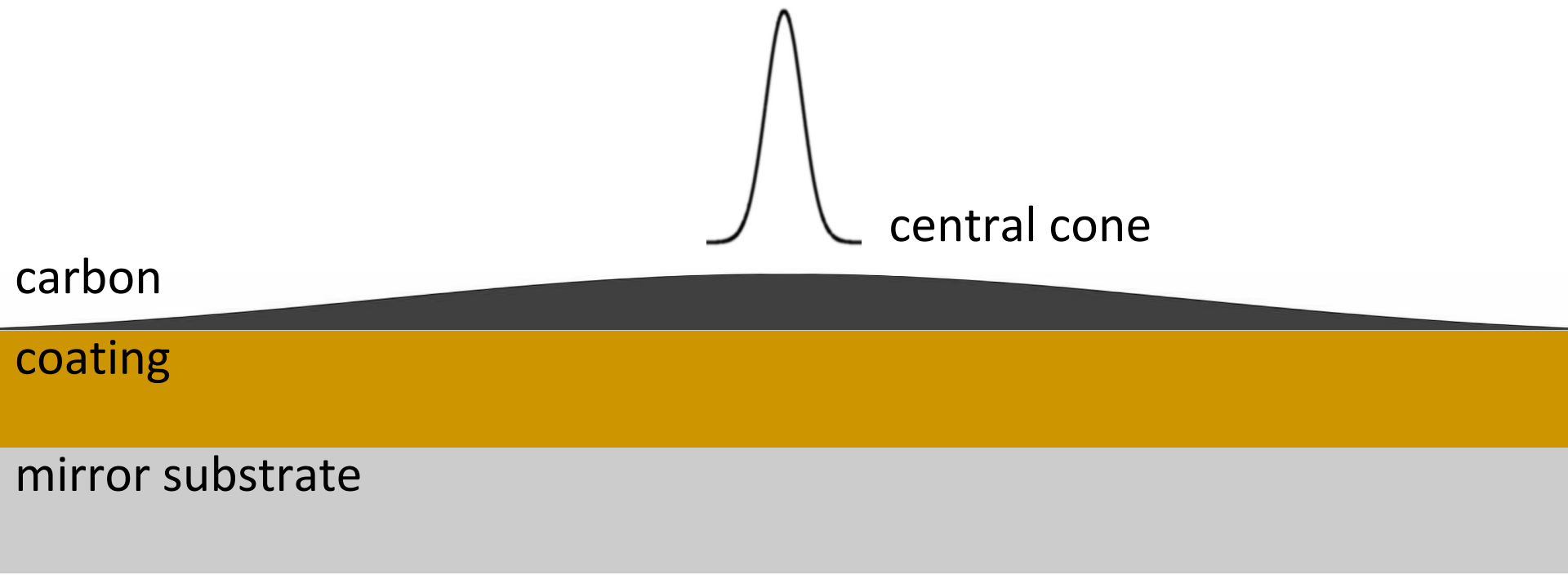
- **Lab-based** visible-light metrology to accelerate development
- **At-wavelength** testing to guarantee and refine performance

ALS-U: Phase shift with surface carbon, *worst case*



ALS-U: Phase shift with surface carbon

- If there is carbon, it will follow the beam footprint.
- The monochromatic portion, from the central cone, is *much smaller.*
- For phase shifting, the critical metric is the *relative carbon thickness* across the central portion of the beam.



SLAC: Observing carbon contamination effects

After 6 years of operation

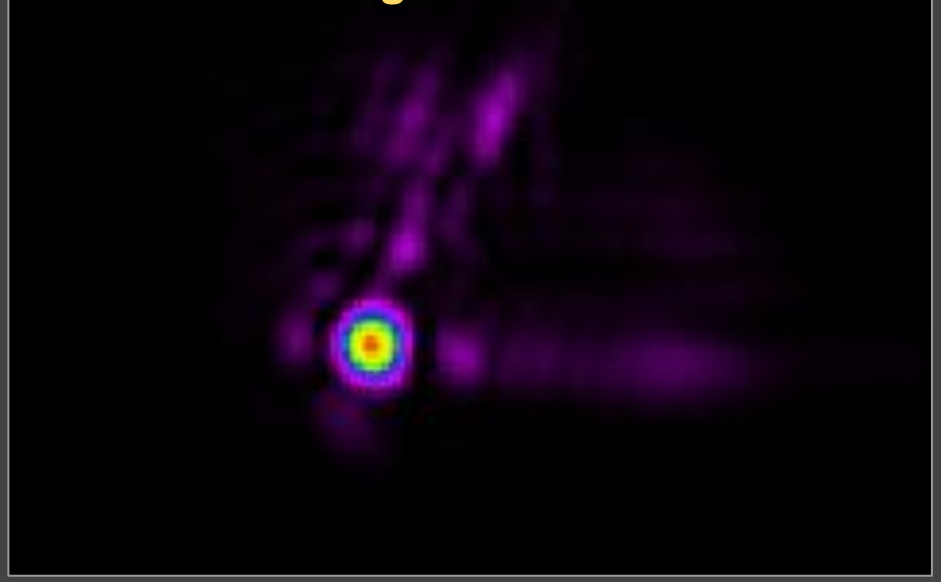
HXR: 2 nm of C, no measurable effect on the beam.

SXR: 50 nm of C on the KB mirrors, 3 nm rms roughness

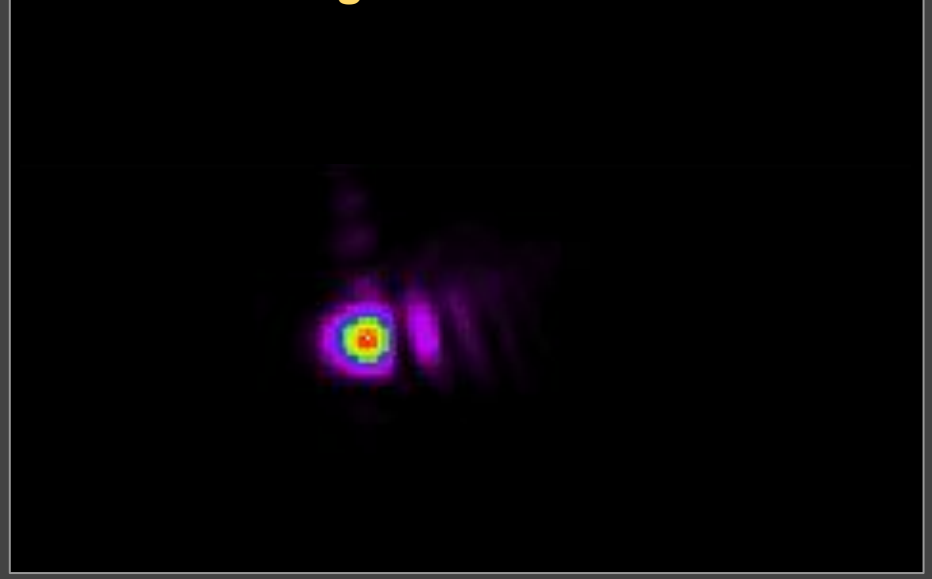
- Based on 50 nm shape error: expected **Strehl Ratio << 0.1**
- Based on 3 nm roughness: expected **Strehl Ratio = 0.6**

→ **Observation** (and simulations) are in agreement with the "roughness" effect only

***Before cleaning** the KB mirrors*



***After cleaning** the KB mirrors*



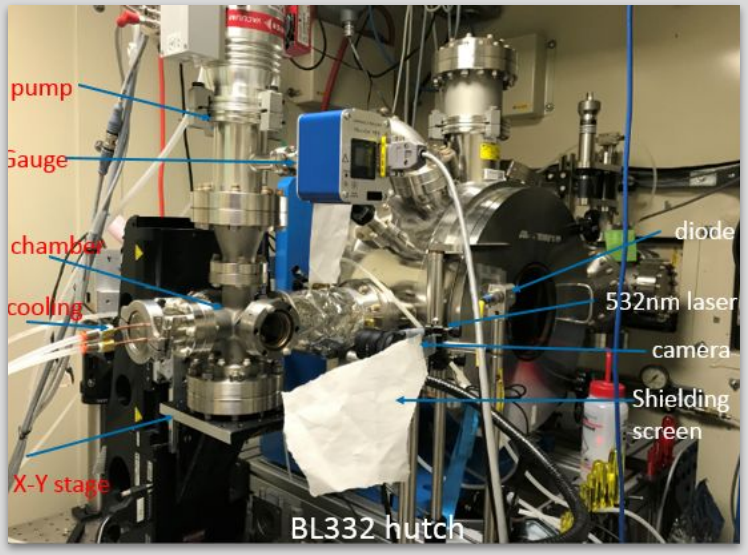
ALS-U: Carbon Strategy

- Chamber preparation: baking, passivation, coating, etc.
- Careful selection of in-vacuum materials
- Minimization of surface area by design
- UHV/cleanroom assembly and installation practices
- Oxygen flow (Au coating), or hydrogen flow (Ni coating)

} *Prevention*

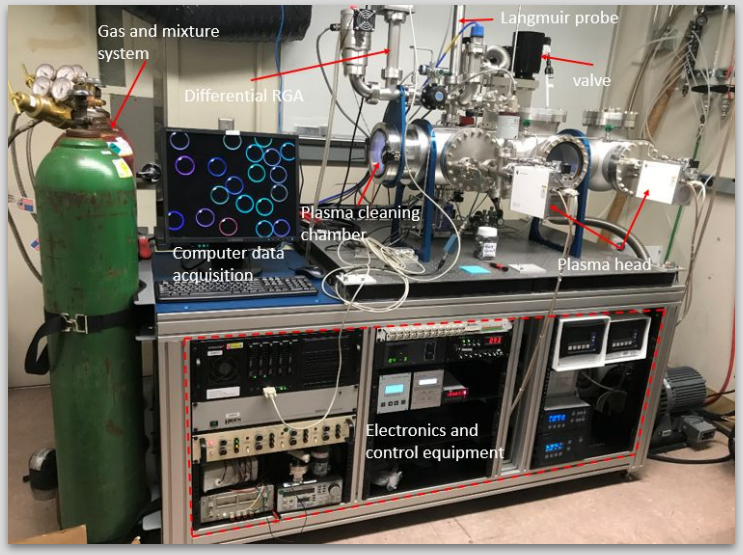
- **R&D** on in-situ plasma cleaning:
  coatings, **mirror temperature**, and **plasma conditions**

} Remediation



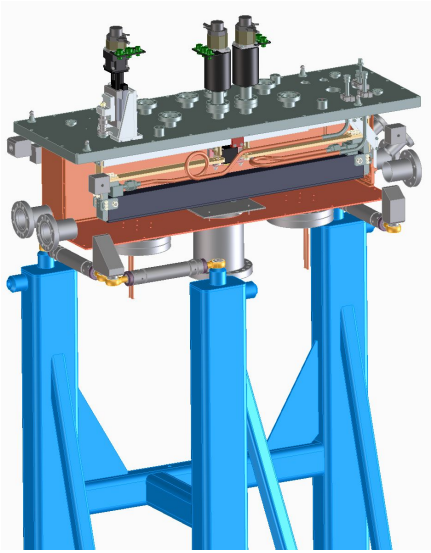
BL endstation for x-ray carbon deposition

ex-situ plasma-cleaning test system

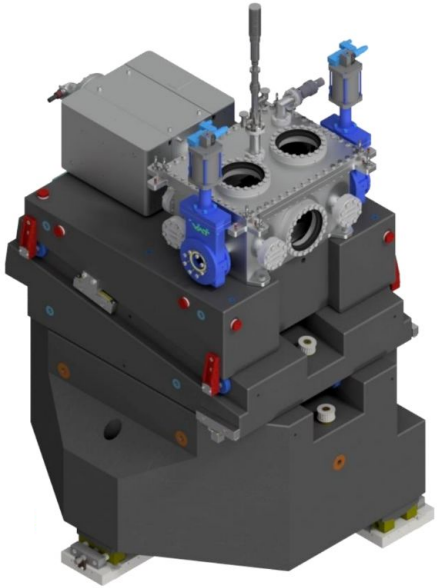


Special Concern: Mechanical Stability in the presence of cooling

Challenging BL environments, but stability specs are within reach: Examples



ALS PX Beamline H2O M1s
(900 mm) < 25 nrad



SIRIUS LN M1
< 20 nrad, 140 Hz stand,
250 Hz mirror mount

AXILON LN M1
@ XFEL.EU < 25 nrad

Design guidelines:

- Minimize Degrees of Freedom, prioritize “align and clamp”
- Leverage granite pedestals → high eigenfrequencies, thermal stability
- Adopt a strategic layout: What goes on the atmospheric side / what goes in the vacuum.

Special Concern: Cryo-Mirrors Thermal Performance

For larger optics: Low strain-per-unit-length requirements constrain solutions to the "thermal sweet spot." *(Req'ts may be looser for smaller, ALS-U optics.)*

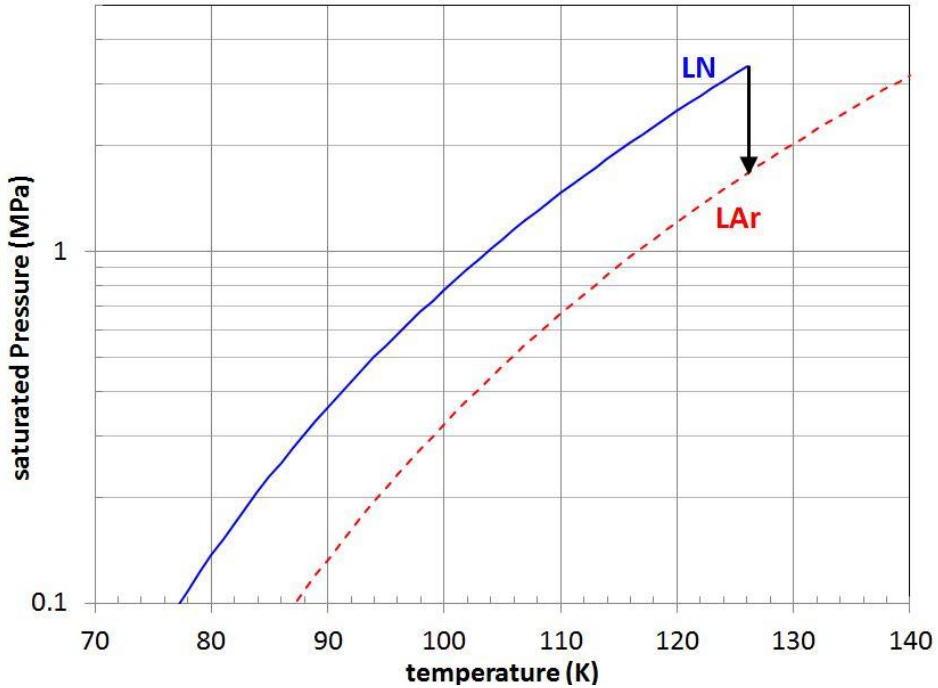
- ***T* sweet spot** → minimal optical strain → ~130 K typical (Near zero CTE point.)
- **Target temperature higher than *T*(LN2)** → imposes special design challenges for heat exchanger
  - Thermal & mechanical weak-link designs
  - Compensatory heating
  - Alternative cryogens

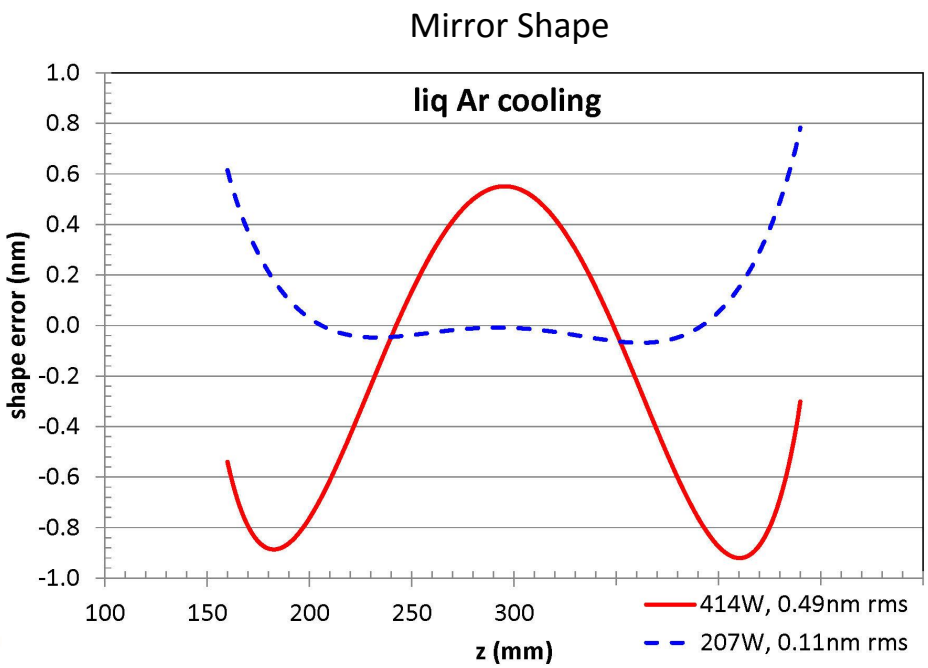
Some technology developed to maintain *T* sweet spot in cryo-mirrors may crossover to multilayer monos and possibly DCM application (e.g., low strain manifolds, alternative cryogens, cryo-metrology.)

Special Concern: Cryo-Mirrors Thermal Example

Shape performance by exploiting thermal sweet spot:

- **Liquid Ar** working fluid ($P_{Ar} \simeq 0.5P_{LN}$; $T_{wetwall} \simeq 126K$ needed for sweet spot)
- 200–400 W & 0.7–1.4 W/mm^2 deposited power
- ≤ 0.5 nm rms (photon weighted) shape error
- equivalent shape performance with LN requires $T_{LN} \simeq T_{crit}$ & $P_{LN} \simeq 34$ bar





Facility-specific near future needs

APS / APS-U

- Cooling of multilayer monos under power load from **two undulators in series**.
- Post APS-U: possible **upgrades to cryo-cooled mirrors** to handle more power load.
- Advances in cryo **could improve crystal monochromators**

ALS / ALS-U

- Cryo-cooling solutions that **maintain performance** over a wide operating range.
- **Metrology at cryo temperatures**, for development
- **In situ carbon-cleaning** tools and protocols
- **Adaptive x-ray optics** coupled to **WF sensing**.

NSLS-II

- SXR beamlines use **internal water cooling**:
  - Possibility of failure
  - Limited mirror performance
- **Cryo-cooling** for NSLS-II ultimate performance is a very interesting option.
- Possible interest also for the **future soft x-ray beamlines** under the new NSLS-II MIE.

LCLS / SSRL

- **Mirror shape-error control** for higher power LCLS-II and upgraded SSRL applications.
- Extension of **cryo heat exchanger tech.** to enhance DMM and perhaps DCM performance.
- **Cryo delay line** for LCLS-II
- Implementation of **adaptive cooling on most** of the LCLS-II optics (no cryo)

Facility expertise and capabilities

APS / APS-U

- Laboratory optical metrology
- At-wavelength metrology for HXR
- FEA modeling and performance simulations
- Beamline testing and validation:
  - Beamline 1-BM for cold temperatures
  - ID Beamline, such as IDEA, for high power
- Adaptive optics development

ALS / ALS-U

- Laboratory optical metrology
- At-wavelength metrology for SXR / TXR
- Thermal/mechanical analysis
- Engineering
- Carbon mitigation R&D
- Development urgency

NSLS-II

- Laboratory optical metrology
- At-wavelength metrology
- Theory and simulation
- Precision engineering and nanopositioning
- Thin films

LCLS / SSRL

- Laboratory optical metrology
- At-wavelength metrology
- Thermal/mechanical analysis
- Beam line system engineering
- Cryogenic monochromators
- Thermal deformation tests (using IR lasers)

Summary of Cryo Challenges

- **Distortion** of mirrors on cooling due to
  - intrinsic stress in Si
  - coupling to cooling manifolds
  - coupling to mirror cradle
- Mirrors in UHV need a reliable **sealing technology**, for robustness
- Establishing the correct **operating temperature** at reasonable pressure (Si is too good a conductor. Reduce the conduction or use LAr)
- **Metrology** of cryogenic mirrors
- **Carbon prevention** and mitigation

Metrology and At-Wavelength Wavefront Sensing

Developing the feedback required for diffraction-limited beamlines and optical systems.

Daniele Cocco, LBNL (SLAC) **Kenneth Goldberg**, LBNL **Tom Rabedeau**, SLAC
Lahsen Assoufid, ANL **Mourad Idir**, BNL

With contributions from

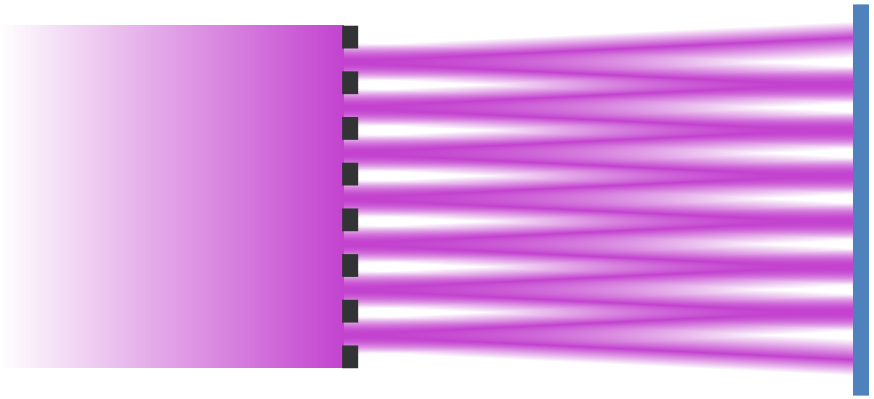
LBNL: Howard Padmore, Valeriy Yashchuk, Ian Lacey, Antoine Wojdyla, Diane Bryant, Peter Takacs

SLAC: Matt Seaberg, David Fritz, D. Morton,C. Hardin, Peter Stefan, Daniele Spiga, May Ling Ng

BNL: Lei Huang, Oleg Chubar, Maksim Rakitin

ANL: X. Shi, W. Grizolli, Y. Shvydko, S. Kearny, D. Shu, M. Wojcik, D. Walko

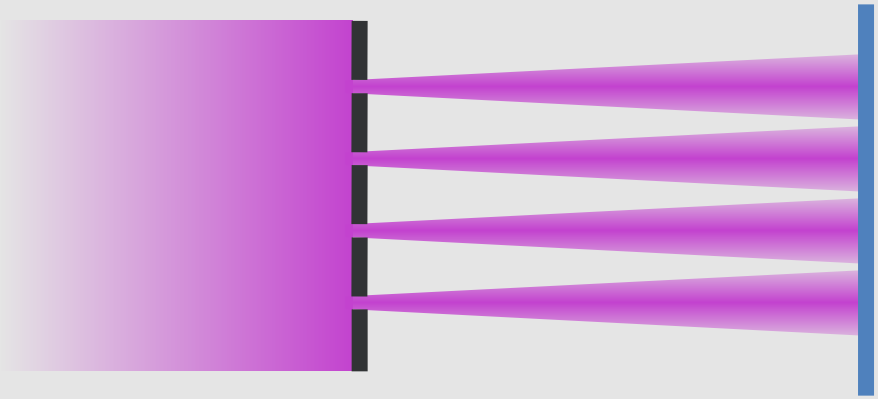
Shearing/Talbot interferometry



grating
self-interference
requires coherence

Naulleau, *J. Vac. Sci. & Technol. B* **18,** 2939-43 (2000)
Grizolli et al., *Proc SPIE* **038502** (2017)
Nagler, *Scientific Reports* **7**, 13698 (20017)
Liu, SRI (2018)

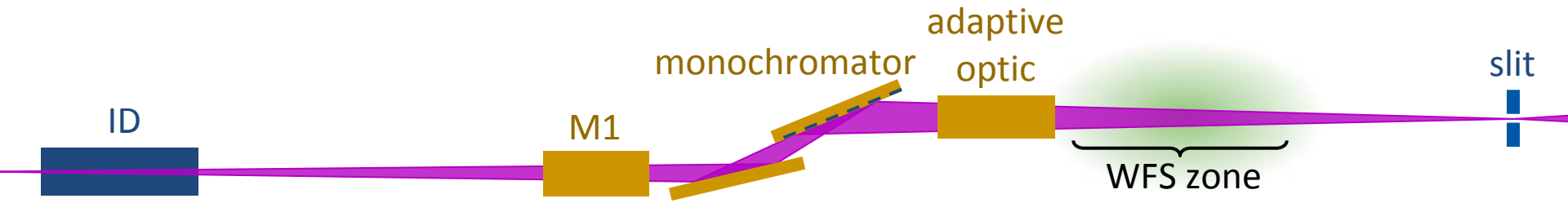
Hartmann wavefront sensor



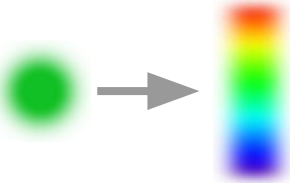
grid
diffraction
low coherence

Mercère, *Optics Letters* **28**, 17 (2003)
Idir, *Nucl. Instr. Meth. Phys. Res. A* **616** (2010)

Wavefront Sensor (WFS) Challenges



- Narrow beams: width = 0.5–2.5 mm
- High power density: W/mm^2
- Broad operating *energy range*: (e.g. 200–2,000 eV, for SXR beamlines)
- Bandwidth upstream of the exit slit: $\Delta E/E \approx 1\%$ from an ID
- Vertical dispersion: smears the wavefront vertically

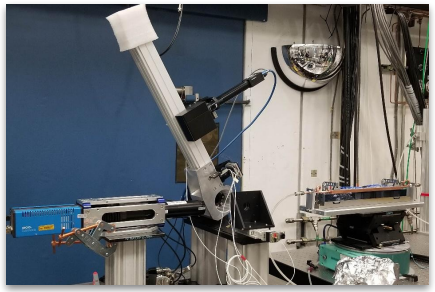


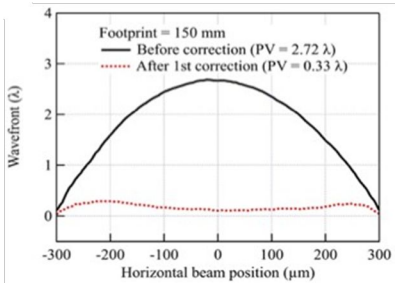
- Real-time feedback: non-invasive, intermittent invasive

At-Wavelength Metrology at U.S. Lightsources

APS / APS-U (HXR)

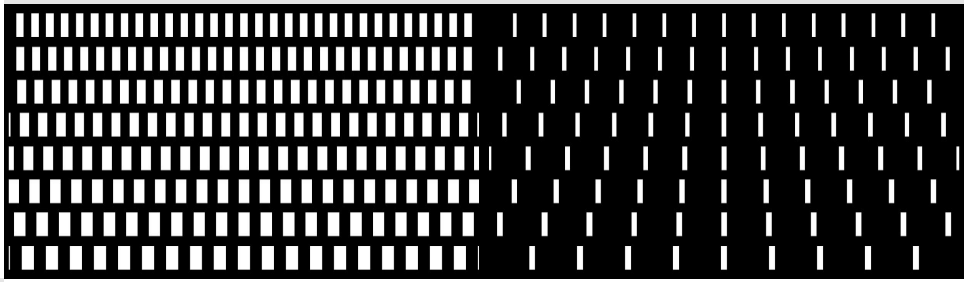
- APS Work on single-grating
- Invasive, non-invasive, REAL tests
- Feedback and analysis open-source code





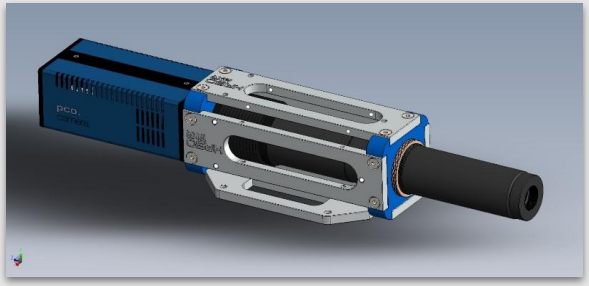
ALS / ALS-U (SXR & TXR)

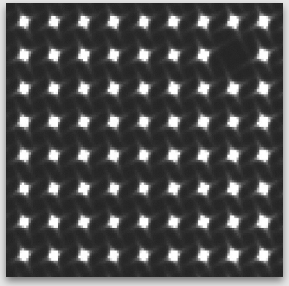
- Prototyping for ALS-U
- Developed multi-grating concept
- Implementing reflection-mode grids/gratings



NSLS-II

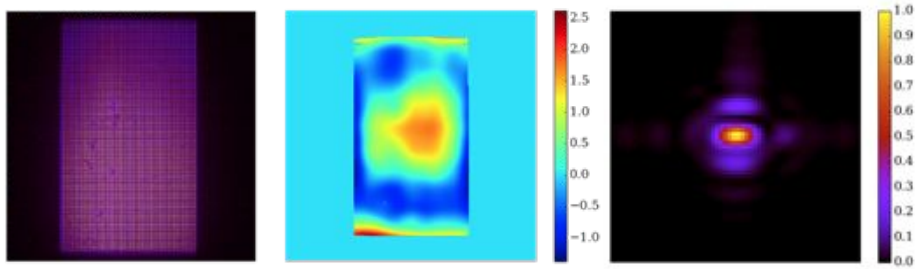
- Hartmann development and testing
- Beamline optimization demonstrations



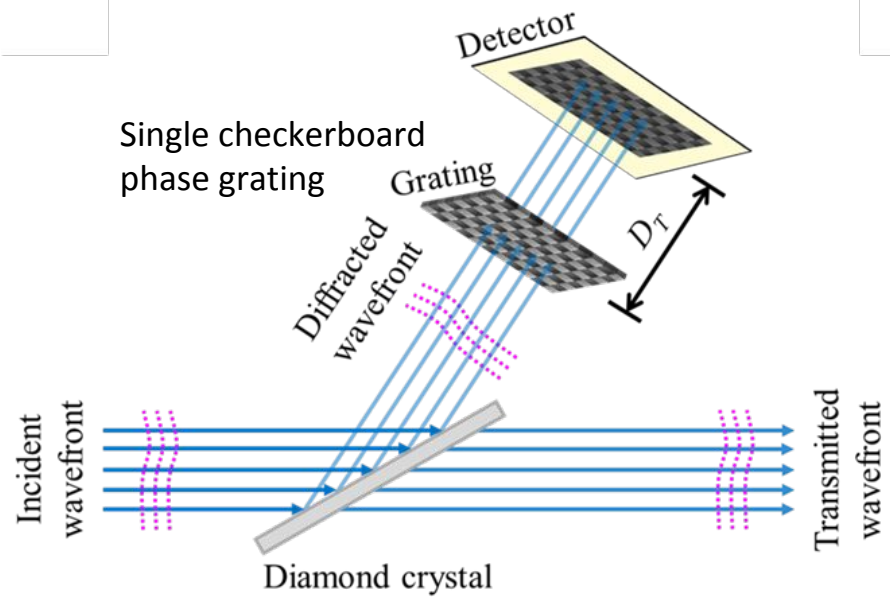


LCLS

- Single-grating shearing/Talbot
- Amplitude and Phase-gratings in transmission
- Removable grids and scintillator



APS/APS-U: Non-invasive WFS for HXR

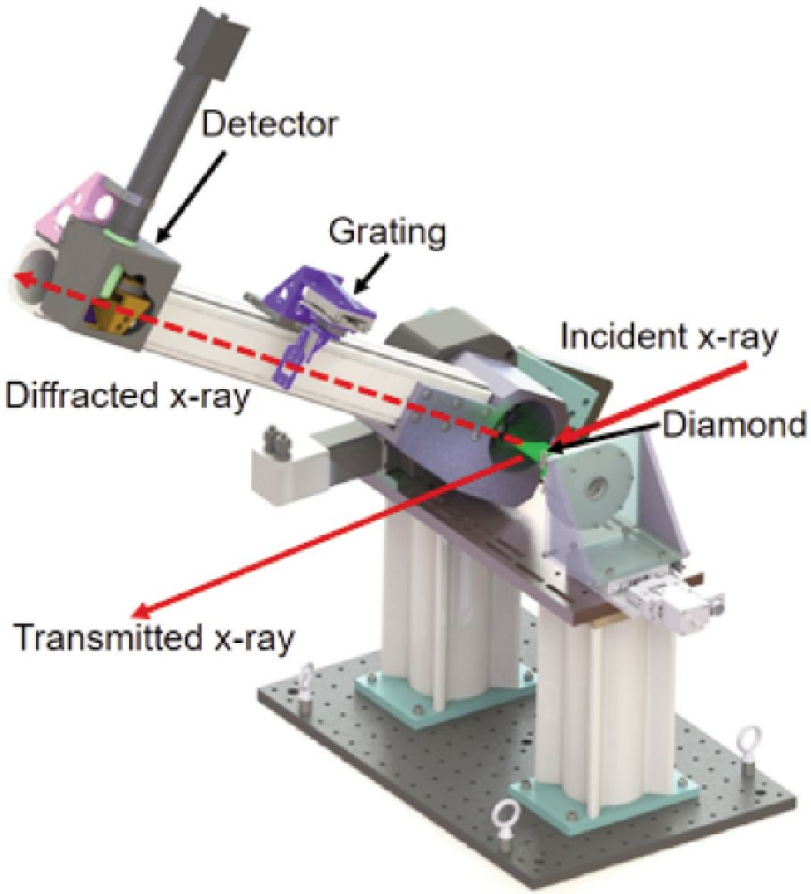


C(111), 100 µm thick

Concept of a hard x-ray wavefront sensor
Using a diamond-crystal beam splitter and a single-grating interferometer.

The relative phase error introduced by the crystal is ~ λ/55 (1.55 Å) at 8 keV.

L. Assoufid, *et al.*, *XOPT* (2018).

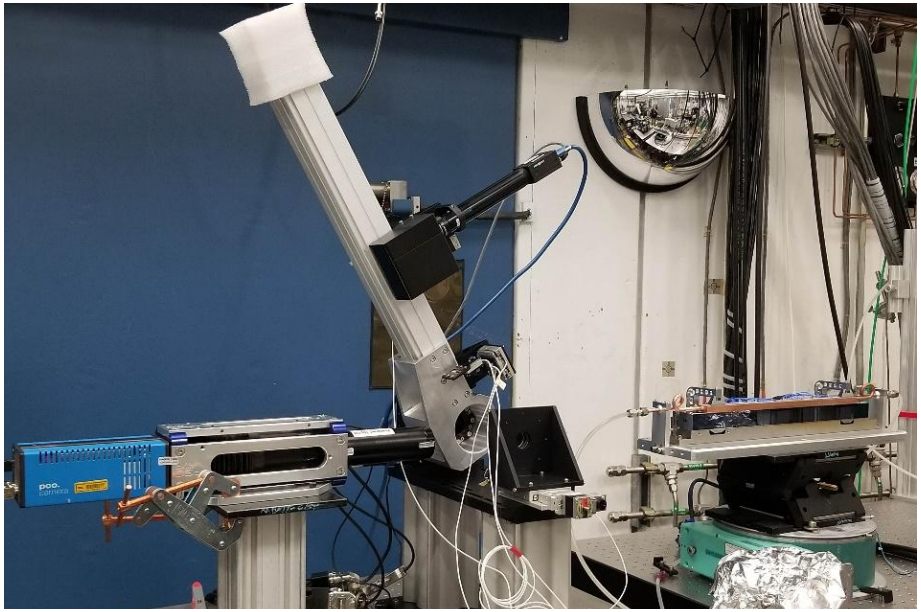


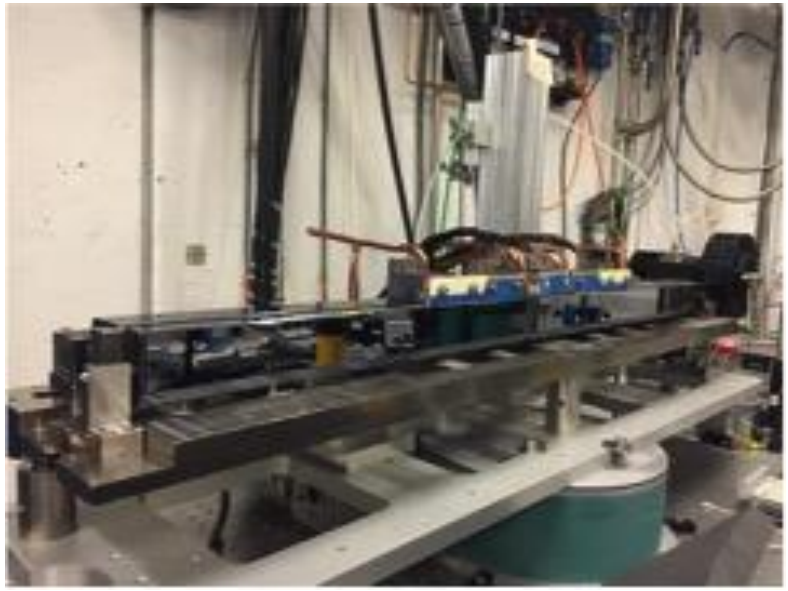
3-D drawing of the prototype assembly

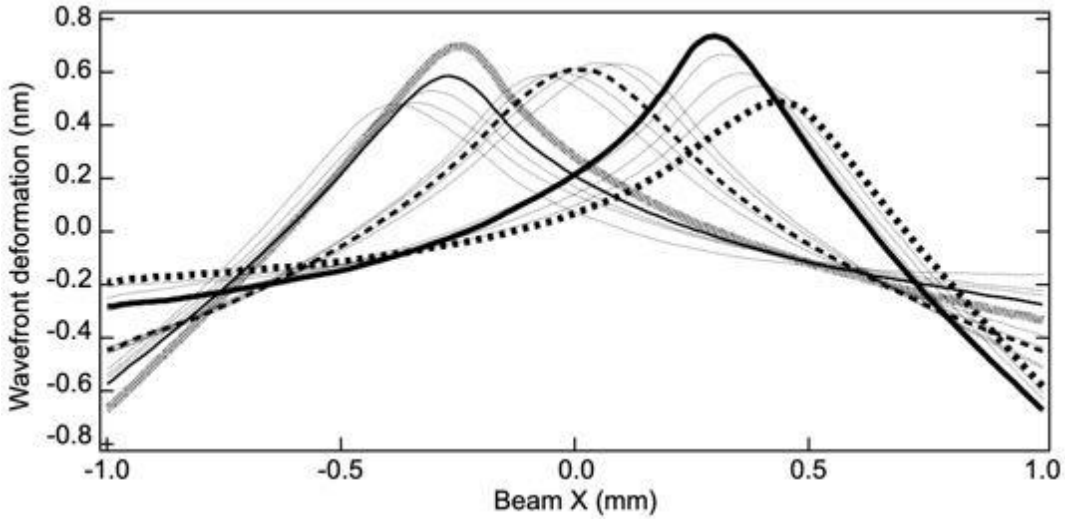
S. P. Kearney, *et al.*, Conference: C18-06-25.9, p.THPH27Proceedings.

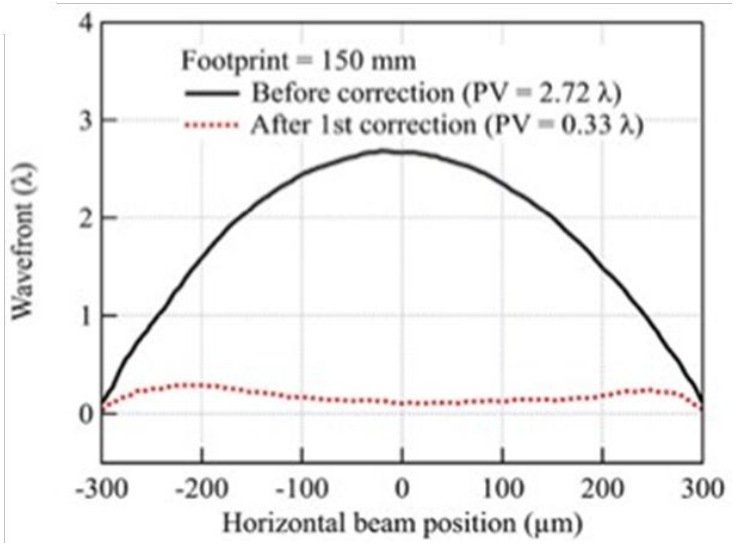
Grizolli, *et al.*, Proc. SPIE 10385 (2017).

APS/APS-U: Non-invasive WFS for HXR

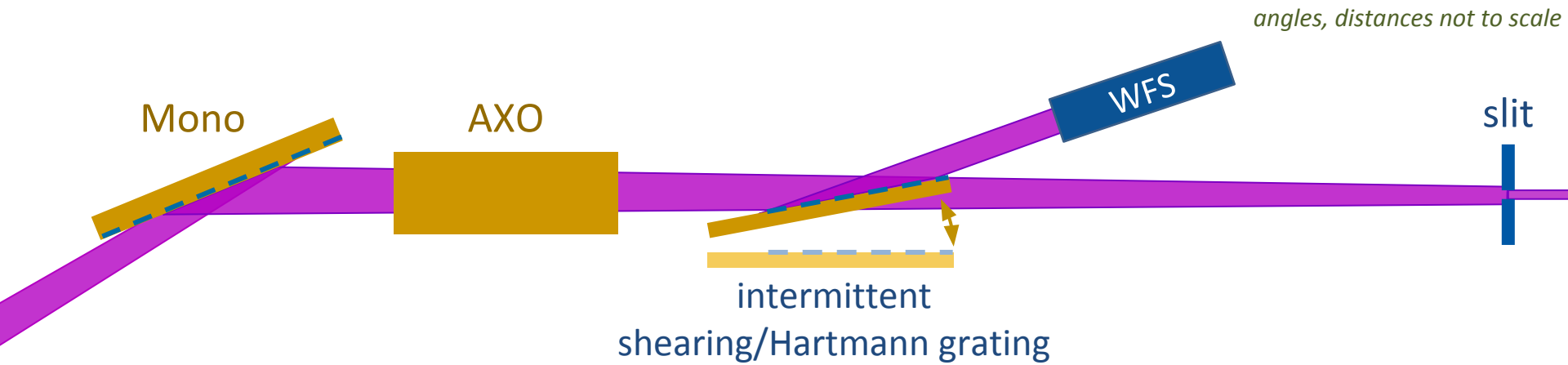








ALS/ALS-U: An intermittent WFS



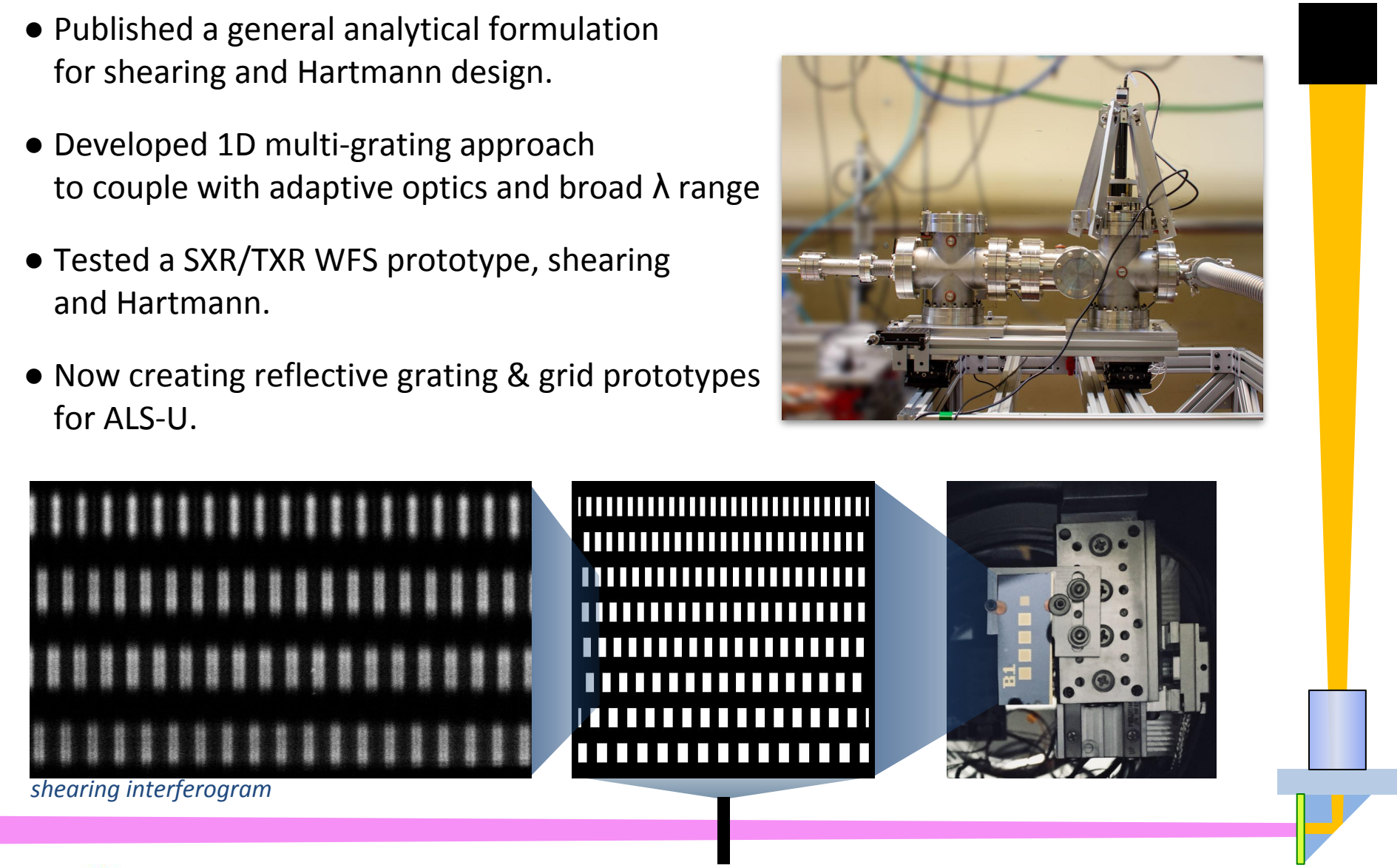
- A fully "non-invasive" wavefront sensor is not yet available for SXR beams
- We plan a fast, intermittent approach based on shearing interferometry and Hartmann wavefront sensing *in reflection mode.*
- Slits can provide fast beam-position feedback for horizontal stabilization.

See ALS-U CDR, and Wojdyla, *et al.* *SPIE* **10760,** 1076003, (2018).

ALS/ALS-U: Prototype work with the WPM project

- Published a general analytical formulation for shearing and Hartmann design.
- Developed 1D multi-grating approach to couple with adaptive optics and broad λ range
- Tested a SXR/TXR WFS prototype, shearing and Hartmann.
- Now creating reflective grating & grid prototypes for ALS-U.

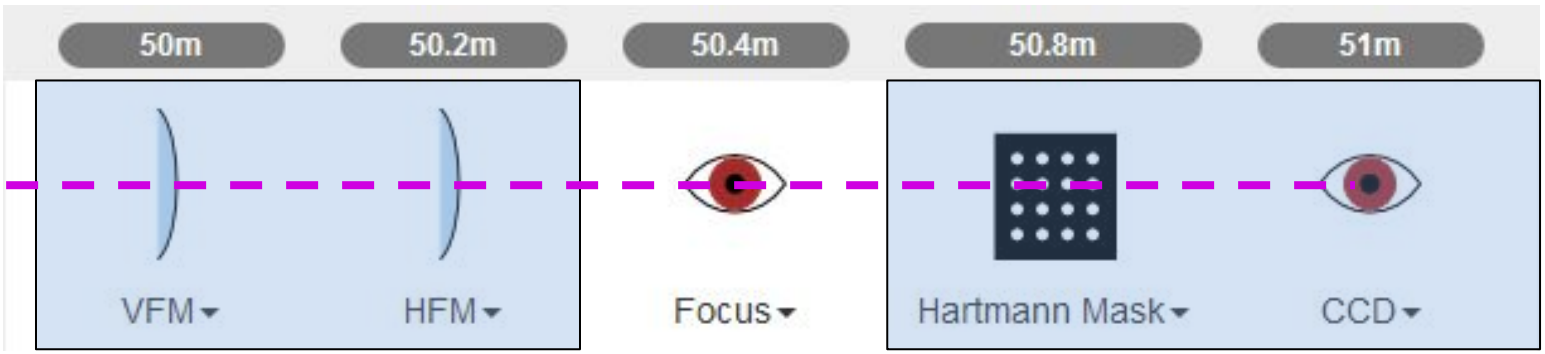
shearing interferogram



See ALS-U CDR, and Wojdyla, *et al.* *SPIE* **10760**, 1076003, (2018).

NSLS-II: At-Wavelength WFS simulation with SRW

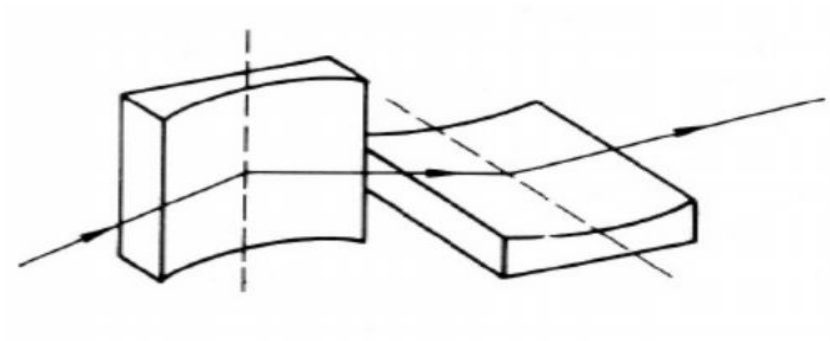
Synchrotron Radiation Workshop



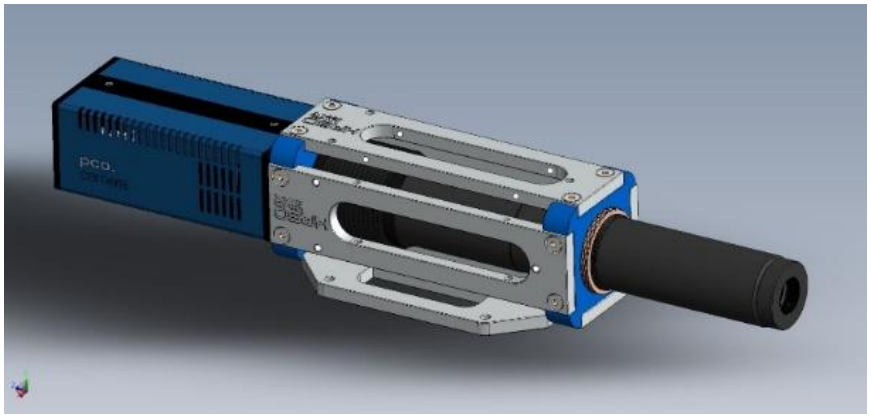
Gaussian Source
E = 9000 eV
$\lambda \approx 0.138$ nm

KB Mirrors

Hartmann Wavefront Sensor
or Grating Shearing Interferometer
Transport-of-Intensity Equation



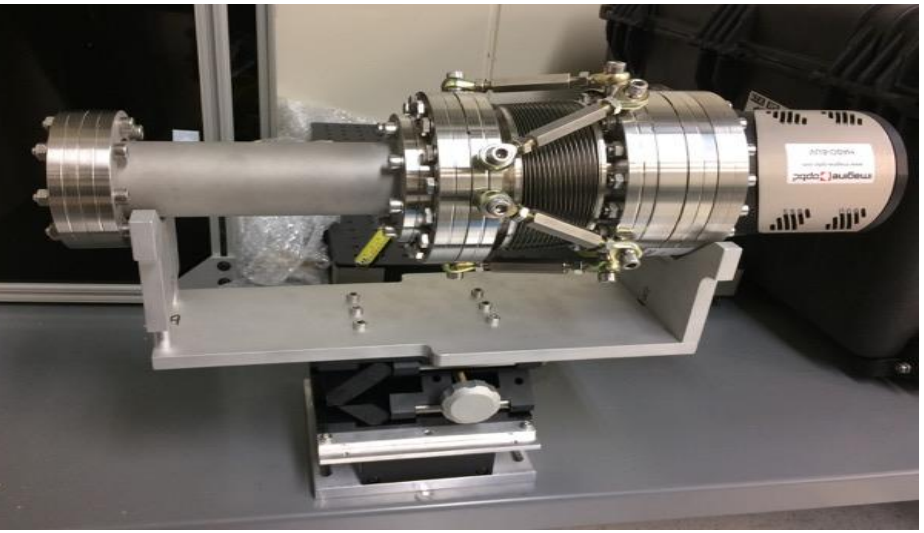
M. Idir, M. Rakitin, B. Gao, J. Xue, L. Huang, and O. Chubar, Proc. SPIE ***10388****, 103880Z (2017).*



NSLS-II: Hartmann Wavefront Sensors (with *Imagine Optic*)

BROOKHAVEN NATIONAL LABORATORY

SXR **direct** detection



- HWS grid = 162.5 µm pitch, 20 µm holes
- Z(grid to camera) = 320 mm
- UHV compatible CCD (13.5 µm pixel size)
  Direct detection

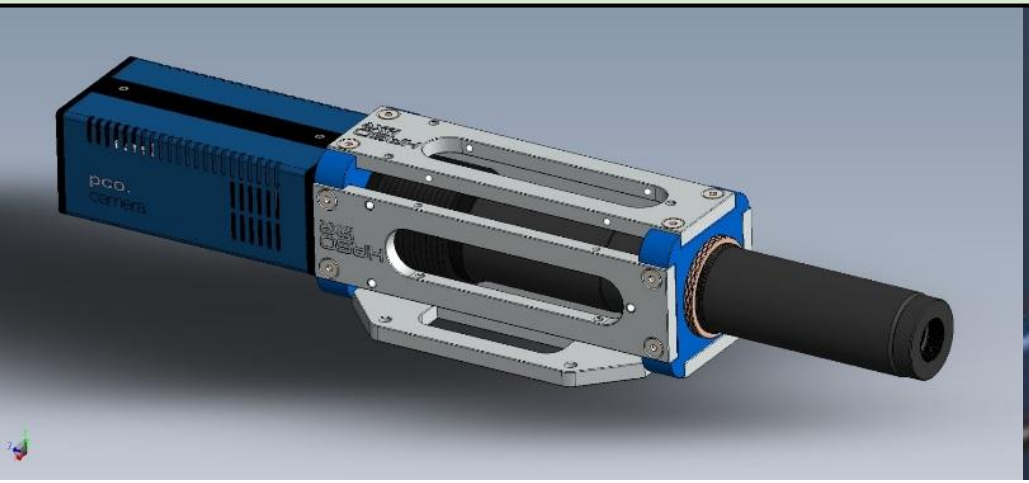
Developed for the beamtimes at LCLS and ALS with Guillaume Dovillaire imagine optic

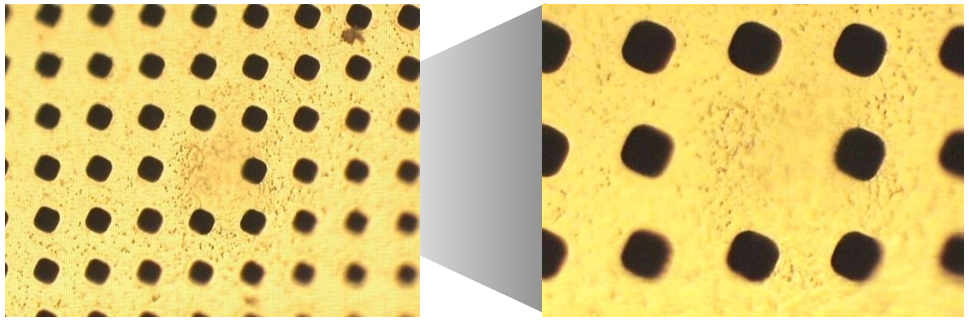
HXR **indirect** detection

- HWS grid = 20 µm pitch, 8 µm holes
- Z(grid to camera) = 150 mm
- CCD camera (7. 5 µm pixel size)
  YAG:Ce scintillator with 5x optimized lens.

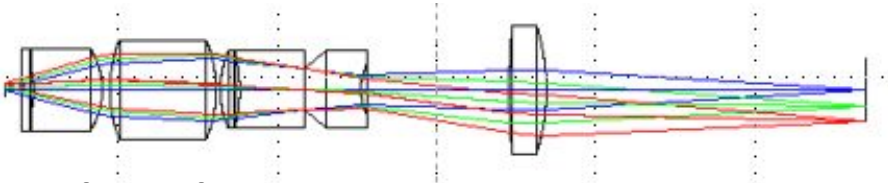
Developed for the beamtime at APS.
Targeting very small x-ray beam

NSLS-II: Hartmann Wavefront Sensors (with *Imagine Optic*)



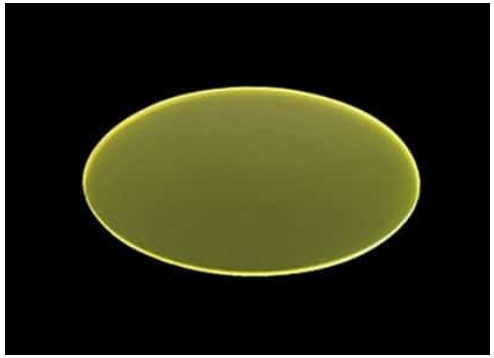


HWS grid = 20 µm pitch, 8 µm holes



Dedicated Lens

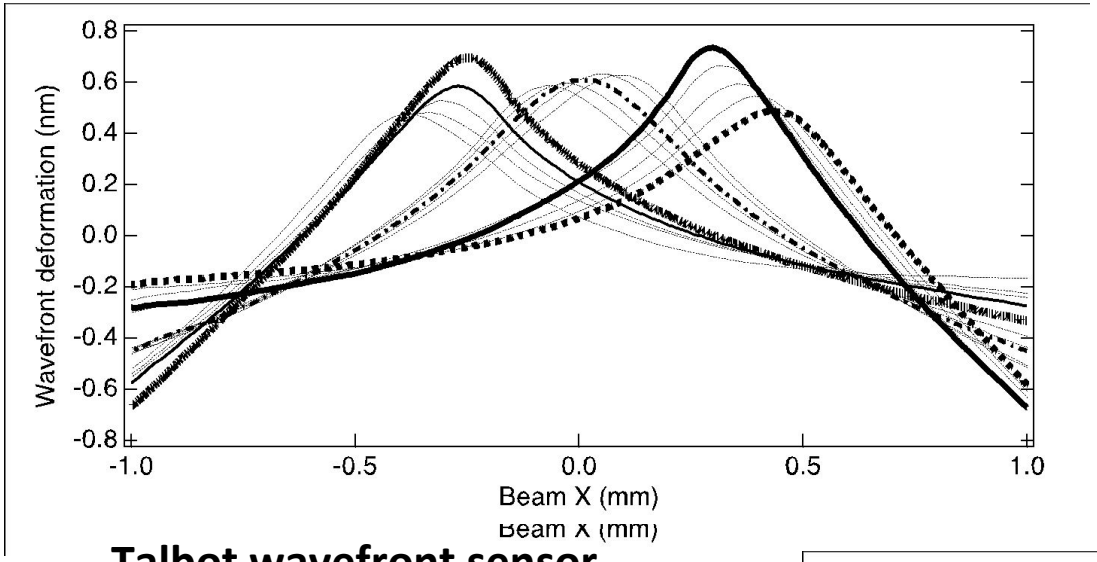
- FOV: 3 x 3 mm²
- Telecentric in object space
- Designed for zero distortion

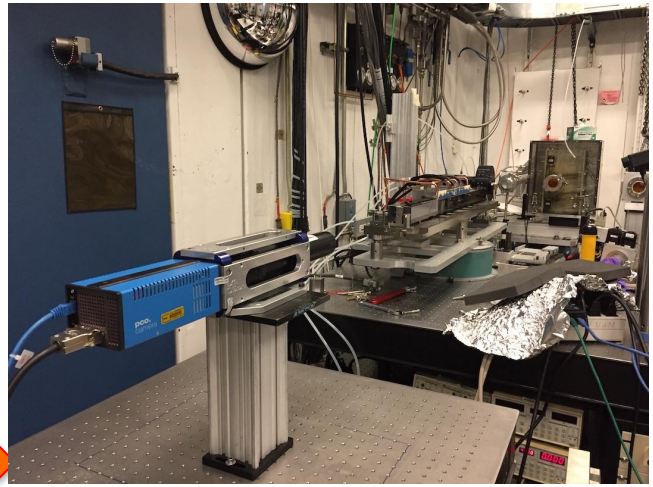


YAG:Ce scintillator

X-ray to visible conversion

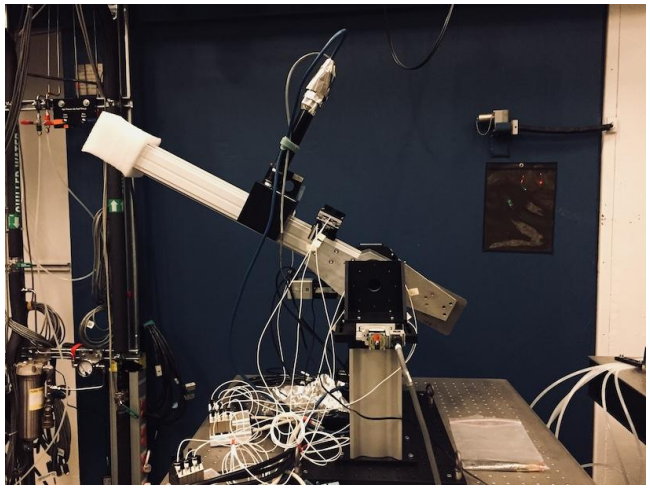
REAL Mirror Tests @ APS 7-ID Bemaline

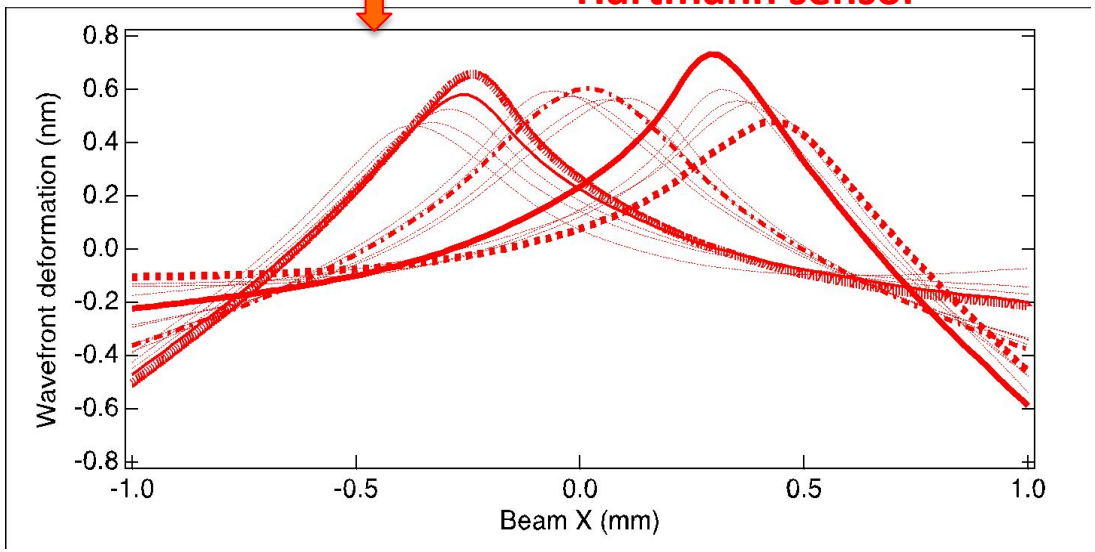




Hartmann sensor

Talbot wavefront sensor

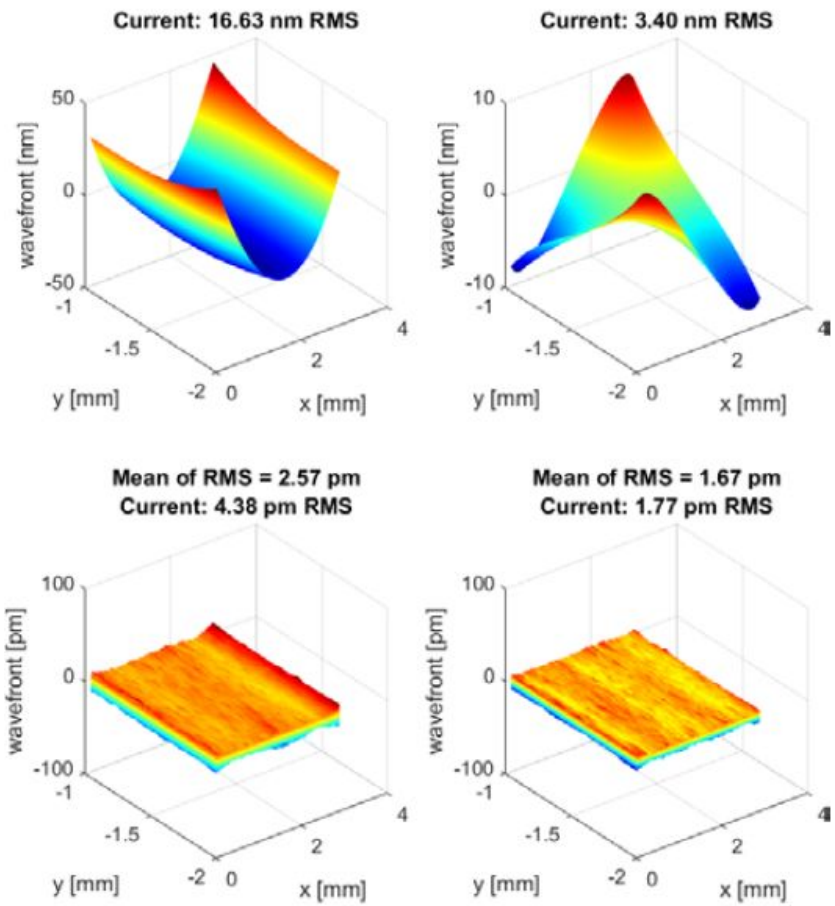




Agreement to picometer level was observed.

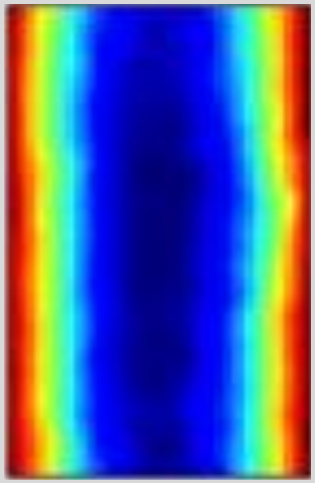
BNL: Hartmann Wavefront Sensor—HXR

E = 12.55 keV, λ = 99 pm



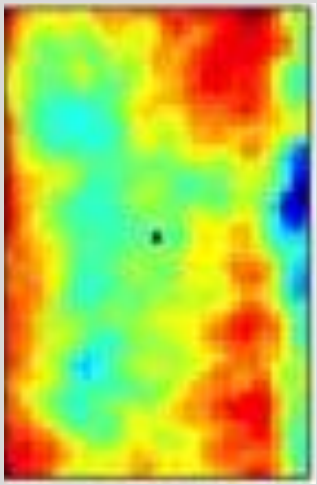
Reproducibility ~λ/59 rms

Results with the REAL Mirror



Residual 115 pm RMS
389 pm P-V

Like a **40 nm P-V** thermal bump



Residual 15 pm RMS
112 pm P-V

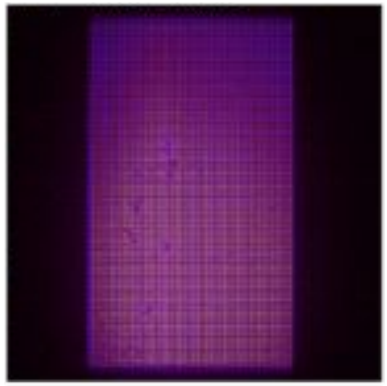
Down to **1.5 nm rms** after correction. (Noise limited.)

LCLS / LCLS-II: At-Wavelength WFS

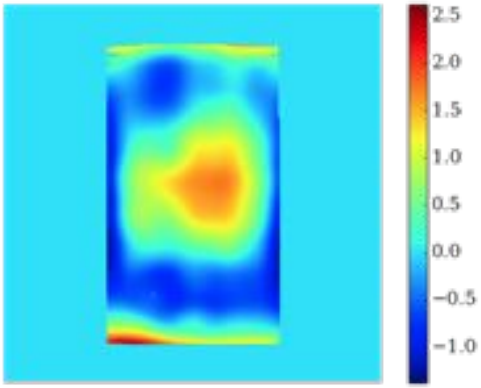
1. Single-grating, phase checkerboard grating.
2. Low-duty-cycle amplitude grating, for high power.

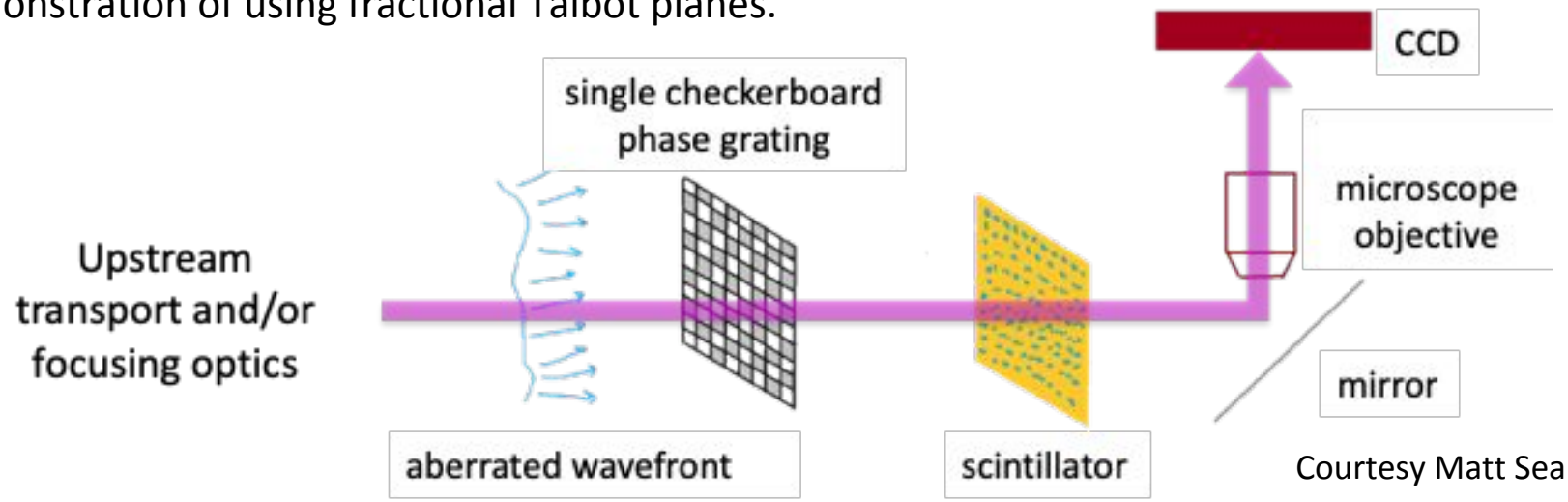
- Comparison of shearing with ptychographic wavefront reconstruction.
- Live feedback for high-order aberration removal through alignment.
- Alignment confirmed with imprints, and peak intensity consistent with original specification.
- Demonstration of using fractional Talbot planes.

single-shot Talbot image



recovered wavefront





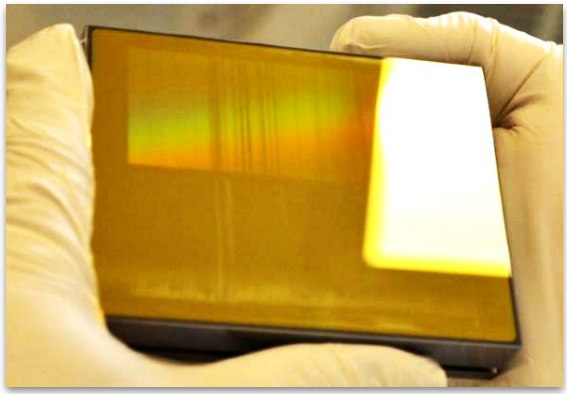
Courtesy Matt Seaberg

Grating/Mask and scintillator **removable** from the beam in vacuum

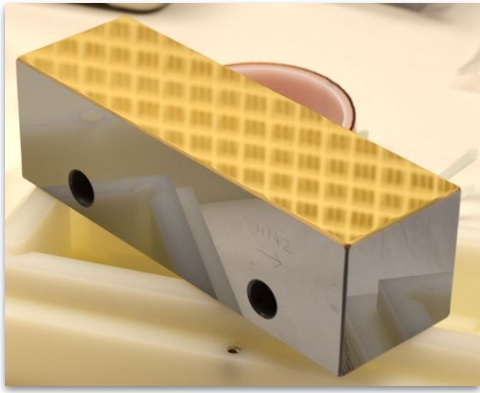
Visible-light ex-situ metrology universal challenges

- Speed: It takes days to measure mirrors.
- Accuracy: 2D and highly curved surfaces push the measurement limits.
  We can not yet rely on vendor metrology.
- Measurement of substrates and mounted optics.
- Registration, and alignment of multiple-elements
- Characterizing Adaptive Optics is *time-consuming*.
- Gratings: Absolute calibration of Variable Line-Space (VLS) gratings is a challenge.
- **Cryo: Measurement of mirrors at cryo-temperatures is new territory.**

FMX Bimorph active mirror



AMBER VLS grating



QERLIN hyperbolic mirror

Visible-Light Ex-Situ Metrology at U.S. Lightsources

APS / APS-U

- Upgrade plan for the LTP:
  - Improve optics board components
  - Implement measurement capability for side- and down-reflecting mirrors.
  - Implement calibration procedures
- Ongoing work on in-situ metrology for the APS Modular Deposition System.

ALS / ALS-U

- 1-year **R&D with Peter Takacs** to upgrade metrology tools.
- **Fresh LTP Redesign** following a deep dive into performance-limiting factors.
- Squeeze more speed from hardware/software.

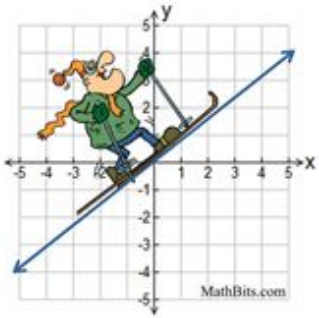
NSLS-II

- Development of sub-nm **stitching interferometry** based on the RADSI principle
- Increase *NanoSurface Profiler* speed & calibration
- Explore new ideas for 2D curved optics metrology tools
- Finalize R&D on *Ion Beam Figuring* (adaptive ion source)

LCLS/SLAC

- Metrology Lab relocated to a more stable environment (Arrillaga Science Center)
- Work on 2D **stitching interferometry**
- Upgrade LTP optics (worldwide collaboration)
- Need to initiate a *Round Robin* to qualify existing instrumentations
- "Installation Fizeau interferometer" is close to beamlines for final verification

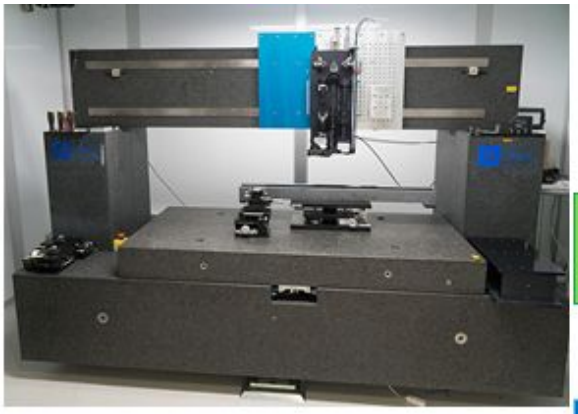
Metrology at NSLS-II: Existing Tools



Slope

LTP/NOM/NSP

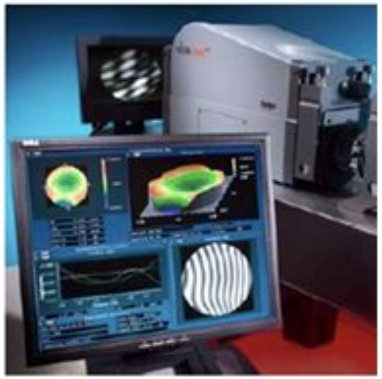
← 800 mm →



Stitching Shack Hartmann

← 1450 mm →

Height

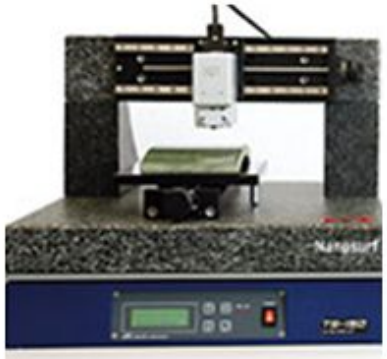


Fizeau Interferometer

100 mm

White Light Interferometer

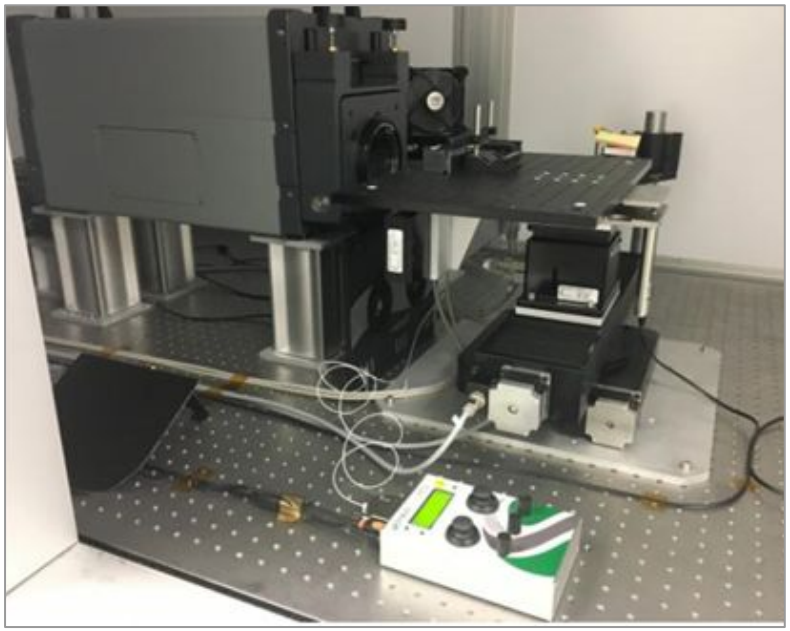
2 mm



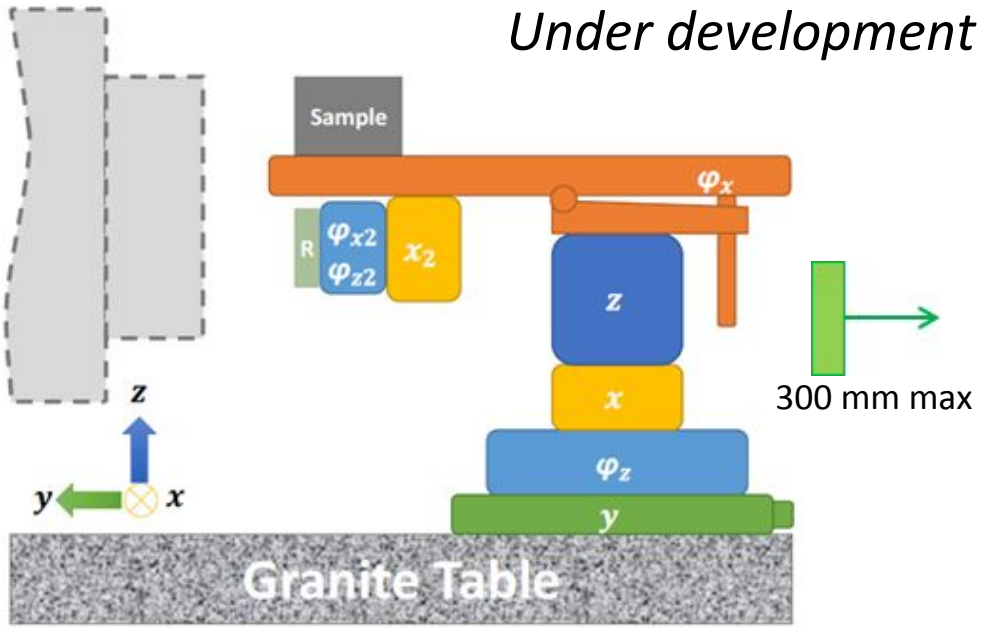
AFM

10 -100 um

Metrology at NSLS-II: R&D Tools and Stitching

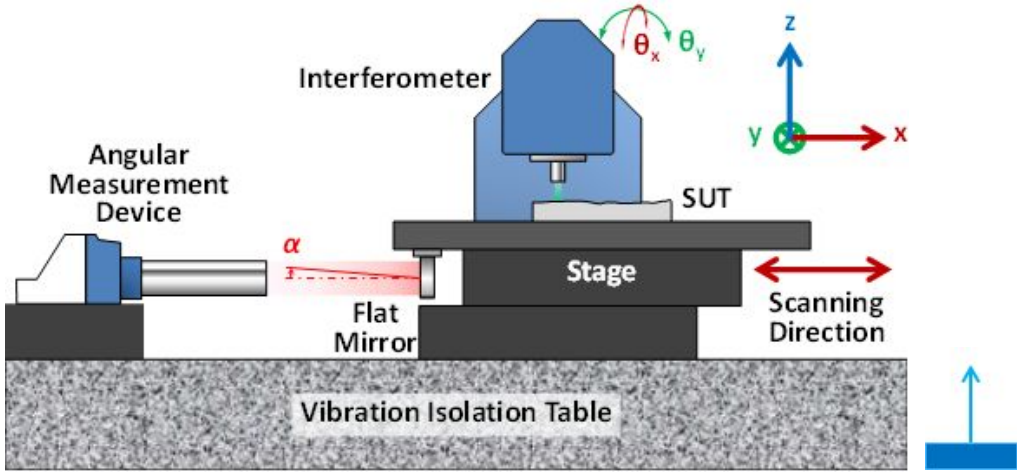


Under development

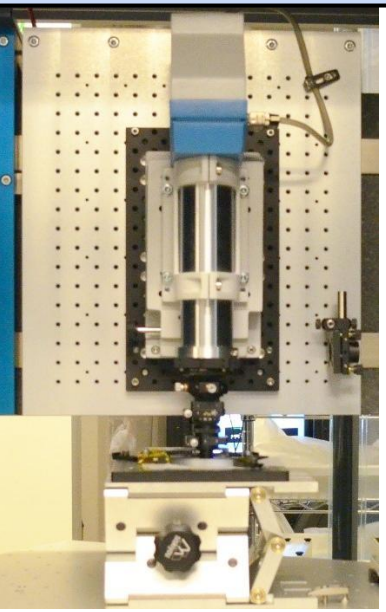


(TOP) Stitching Metrology platform using a 4" FIZEAU Interferometer for SSI and RADSI (2D information).

(BOTTOM) MicroStitching White Light Interferometer coupled with Autocollimator (1D information).

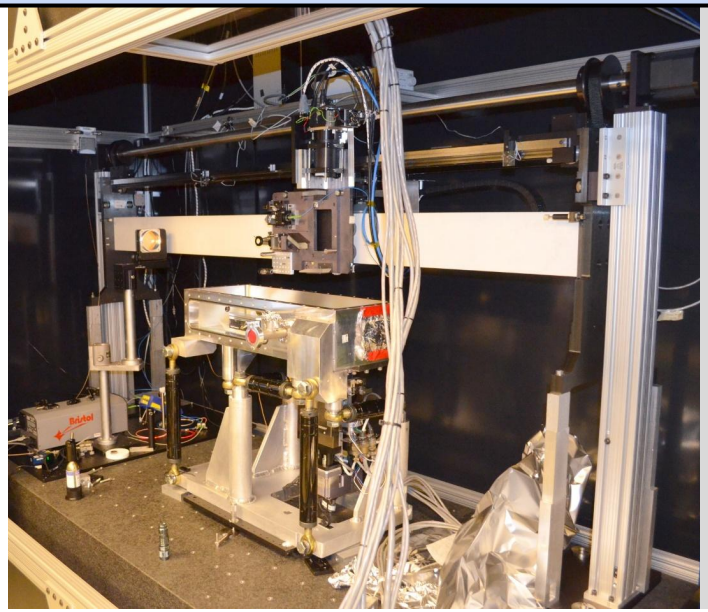


Metrology at ALS / ALS-U: Existing Tools and Upgrade R&D



(OSMS) Optical Surface Measuring System

- 2D surface profiling
- Repeatability < 20 nrad rms
- 4x faster than before



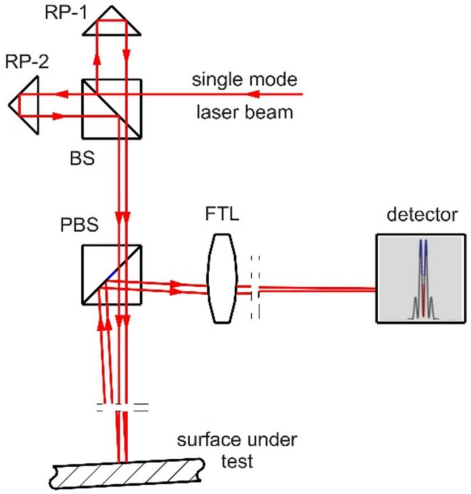
LTP-II: metrology with optical assemblies

- clearance ≤ 26”
- easy access to the SUT (no aperture)
- easy calibration
- open design

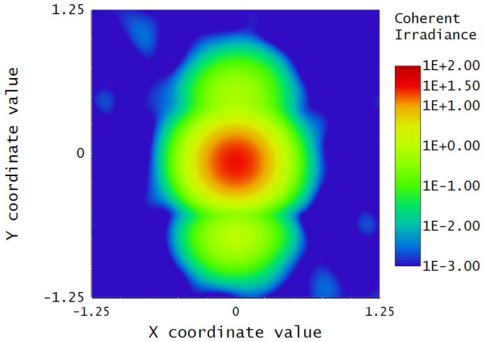
ALS-U Metrology Upgrade R&D Project

Develop plans for the creation of specific new sensor(s) for optical slope profilometers.

- Upgrade existing metrology systems for speed and accuracy
- Enable high-accuracy measurements of VLS gratings
- Support assembly of multi-optic systems



(a)

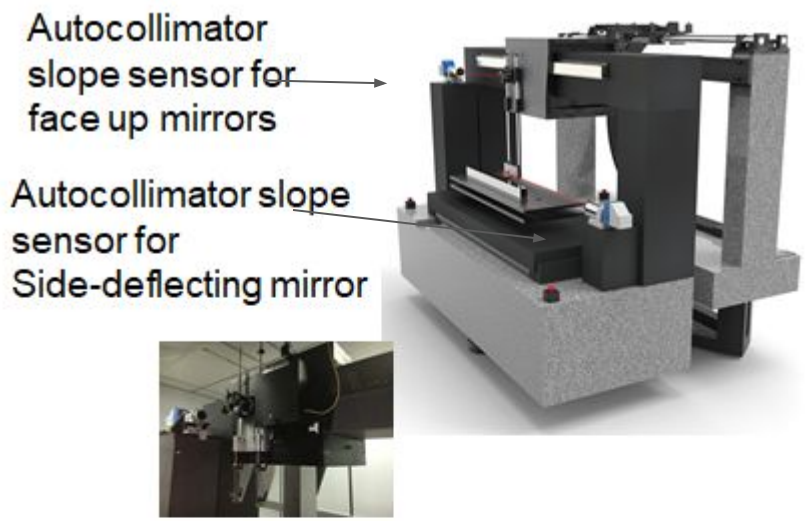


(b)

Metrology at APS / APS-U

APS Dual NOM LTP slope sensors

- **NOM:** autocollimator-based slope measurement (2012)
- **LTP:** accuracy improvements for fast measurements of mirror bender systems (2012)
- Can accommodate 2D interferometer head for **2D stitching (under consideration)**.



APS OSMS: a dual LTP/NOM measuring system

New roughness / microstitching system

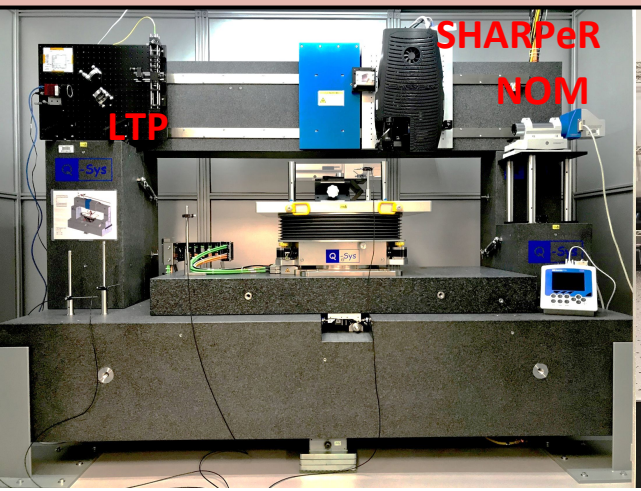
- Commissioned Dec. 2016.
- Coherence Scanning Interferometric (CSI) profiler

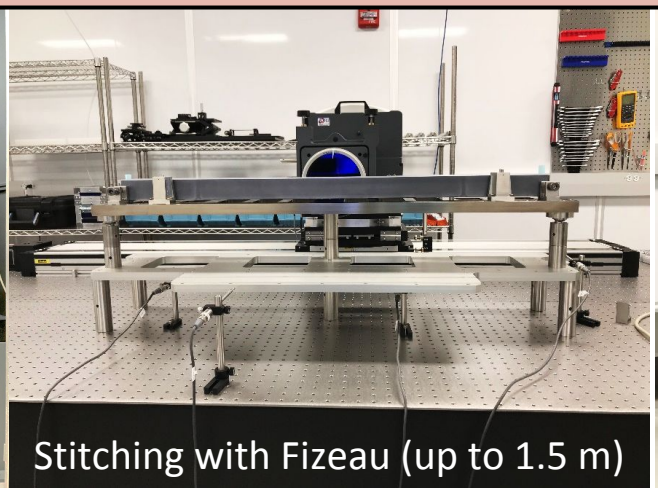
NexView interferometric microscope for surface roughness measurements

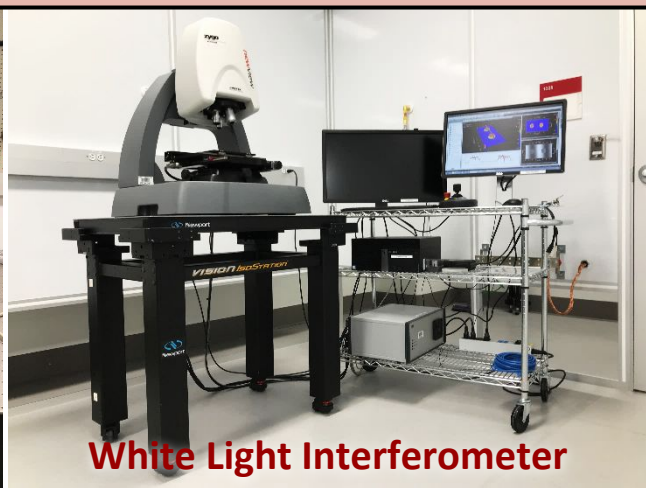
Upgrades to support APS-U

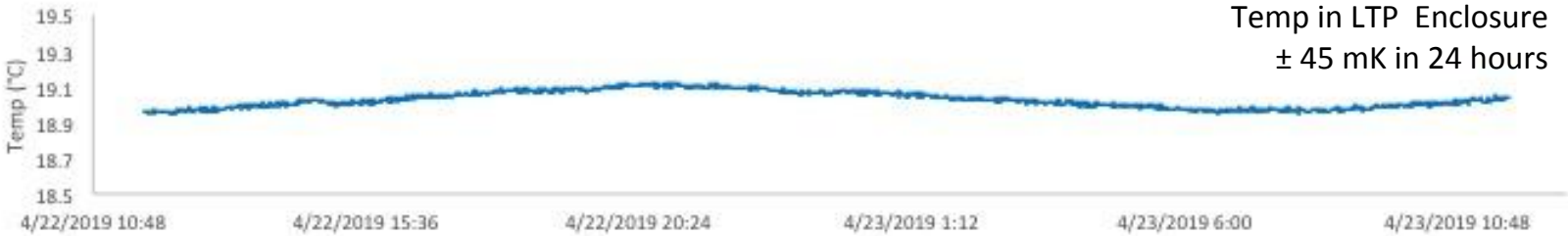
- Capabilities for side- and downward-facing mirrors
- Calibration methods to reduce systematic errors.
- Developing a plan for mirror acceptance tests

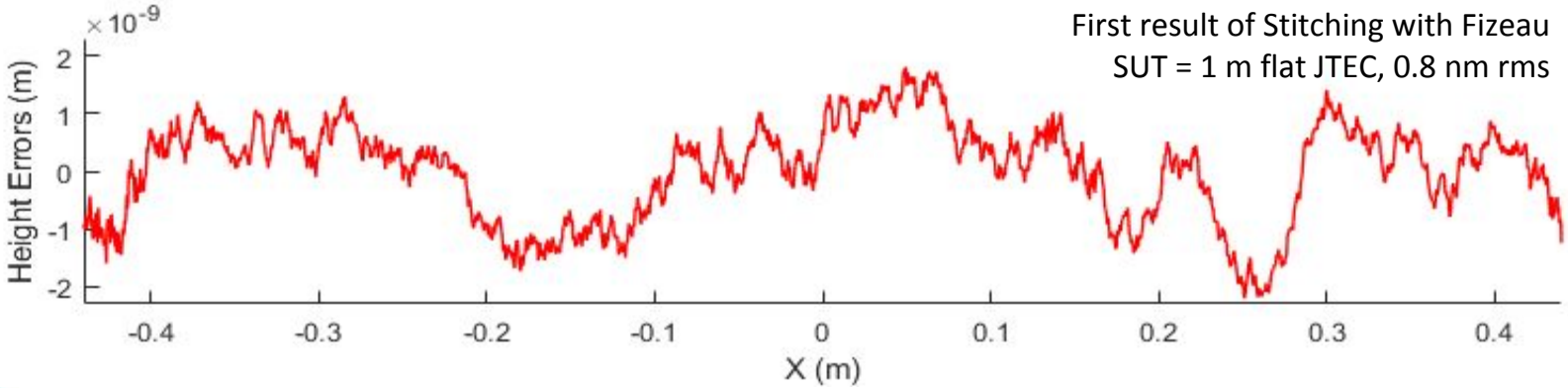
Metrology at LCLS / SLAC (in Arrillaga Science Center)











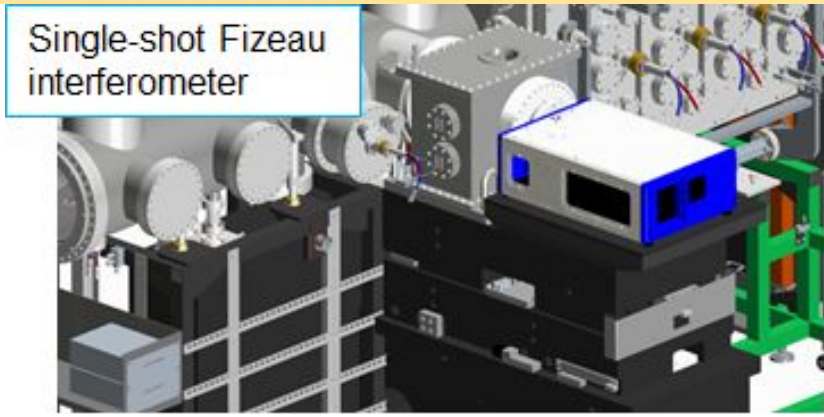
Slide courtesy of May Ling Ng

Metrology Path Forward

Diffraction-limited quality is only achievable with reliable metrology.

At-wavelength wavefront sensing tools

- Need continued development toward **real-time solutions**.
- **Beam diagnostics** is an important topic for Optimal beamline performance.



APS *in situ* metrology design

Optical Metrology

- Optical Metrology = Mirror Fabrication has always followed the x-ray beam quality
- Need **metrology compatible with cryo-cooling** to accelerate development.
  We need to make the necessary step to tackle the cryo mirror challenges

NASA Goddard cryo-metrology

Collaboration has always been key to progress in metrology.

Conclusions

- DOE/BES is currently investing almost $2.5B across the complex in DLSR/FEL upgrades and capability expansions.
- Wave front preservation is central to realizing the capabilities of these new sources, in the presence of high power and a rapidly changing profile on the optics.
- The performance requirements on these optics demands collaborative development of new technologies to meet these challenges:
  - Thermally optimized, low strain, stable cryo-mirrors
  - Ex-situ metrology to support cryo-mirror development and testing
  - At-wavelength metrology for online mirror optimization
  - Environmental control to mitigate carbon contamination

Investment and collaborative development of these technologies is paramount to extracting the full potential of DLSR/FEL sources and maintaining a leadership position in the international light source community.