Advanced X-ray optics for a diffraction-limited source

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Optics and Wavefront Lead, LBNL

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U.S. DEPARTMENT OF ENERGY | Office of Science

ALS-U ADVANCED LIGHT SOURCE

Third Generation Light Source,
by comparison

Future X-ray optics—major concerns

and topics for collaboration

state-of-the-art surface profiles

thermal management

vibration and mechanical stability

carbon prevention / mitigation

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Surface profiles

Required: Sub-100-nrad slope errors in many cases;

sub-50-nrad in others.

A limited number of suppliers, worldwide have the tools & capacity to produce these

- The technology exists
- The metrology is hard to come by
- Capacity limitations could be critical

  - Begin discussions early
  - Acquire/create metrology tools

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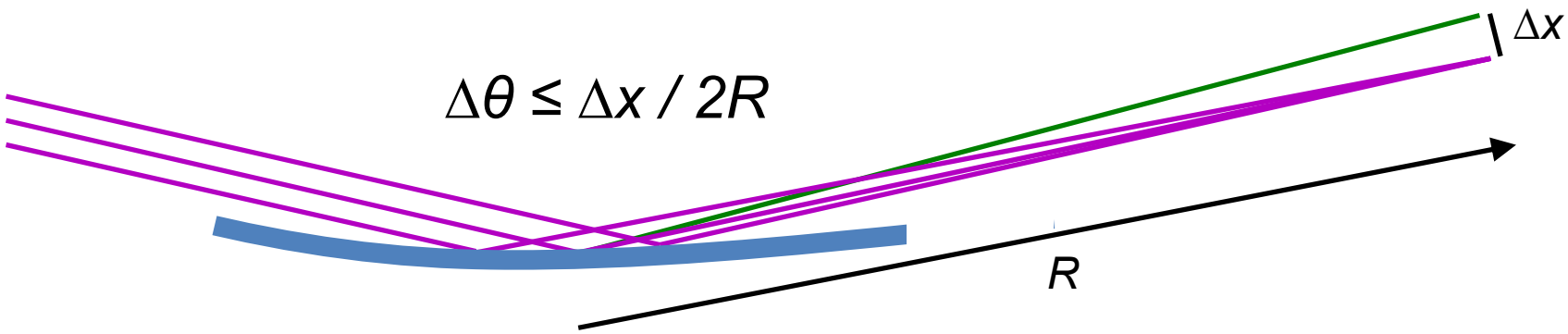
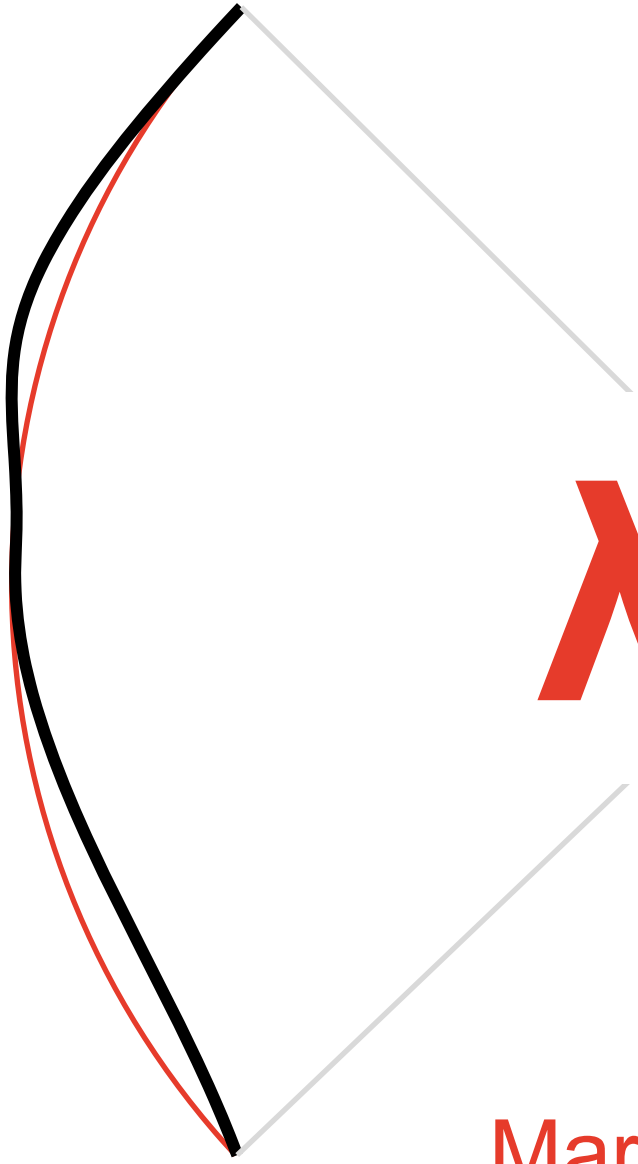
Slope descriptions *are inadequate*





λ/14

Maréchal Criterion:

➔ ***high Strehl Ratio***

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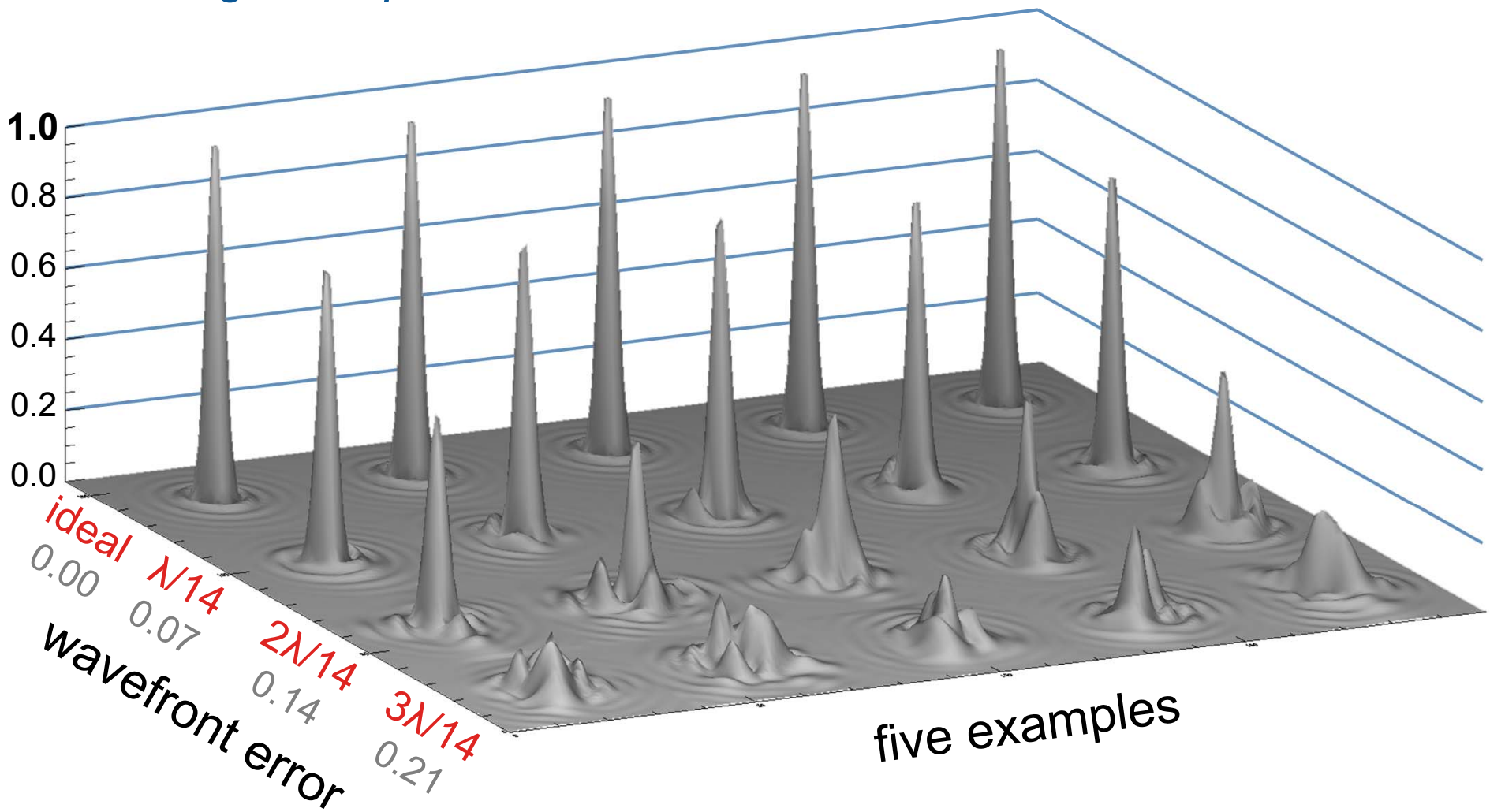
Wavefront errors dictate performance

Focusing examples



Diffraction-limited point source; circular pupil; low-order aberrations

Many sources of wavefront errors

- mirror shape imperfections
- mirror alignment errors & mechanical drift
- clamping deformation
- temperature-dependent stress
- beam-heating thermal distortion
- (cooling) water pressure
- carbon contamination (also attenuation)

Future X-ray optics—major concerns

- state-of-the-art surface profiles
- thermal management
- vibration and mechanical stability
- carbon prevention / mitigation

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Thermal management

Irradiation is concentrated and time-varying w/ λ, $\vec{E}$

ALS-U IDs peak power: *100 W? 1 kW? 3 kW?*

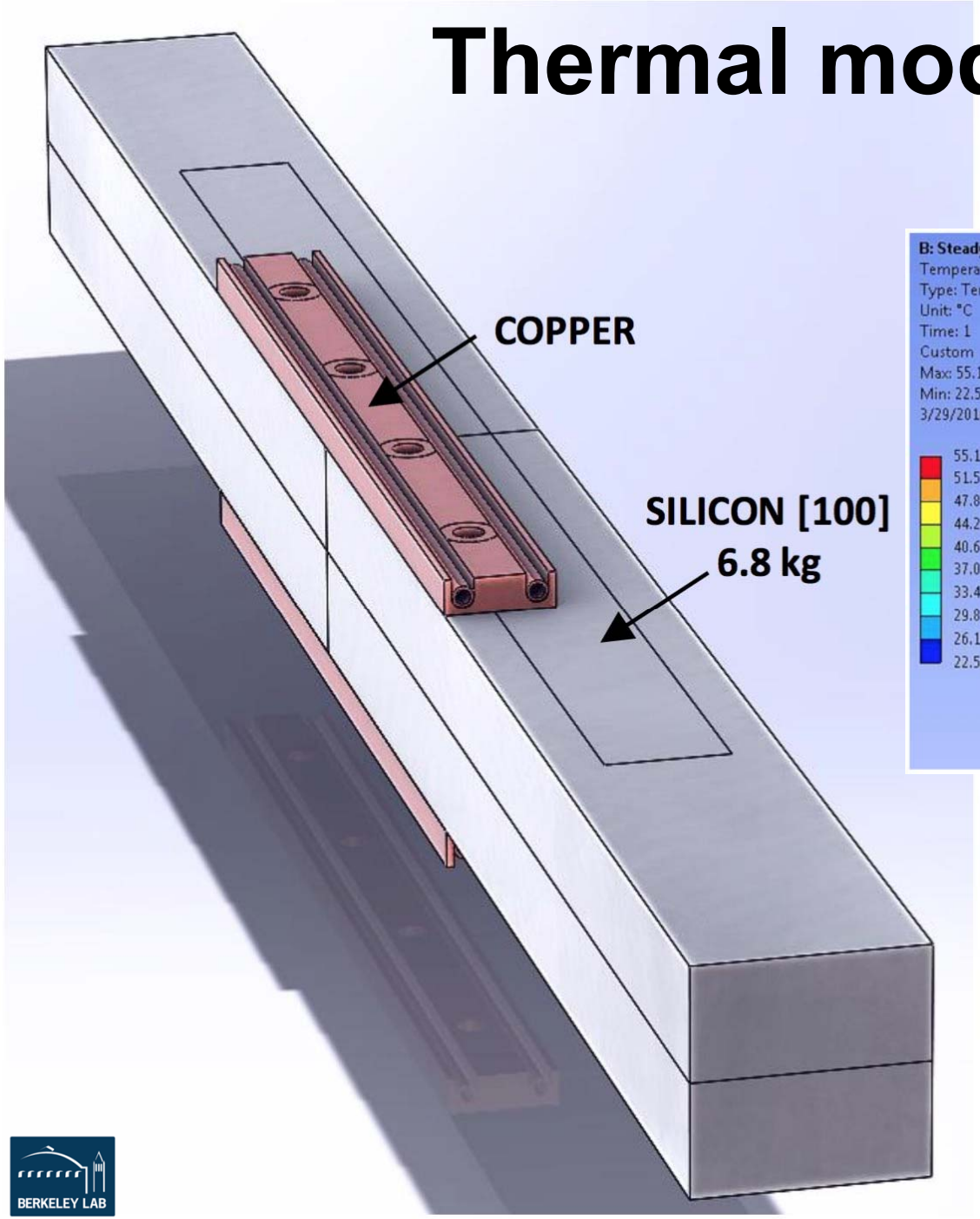
Water-cooling

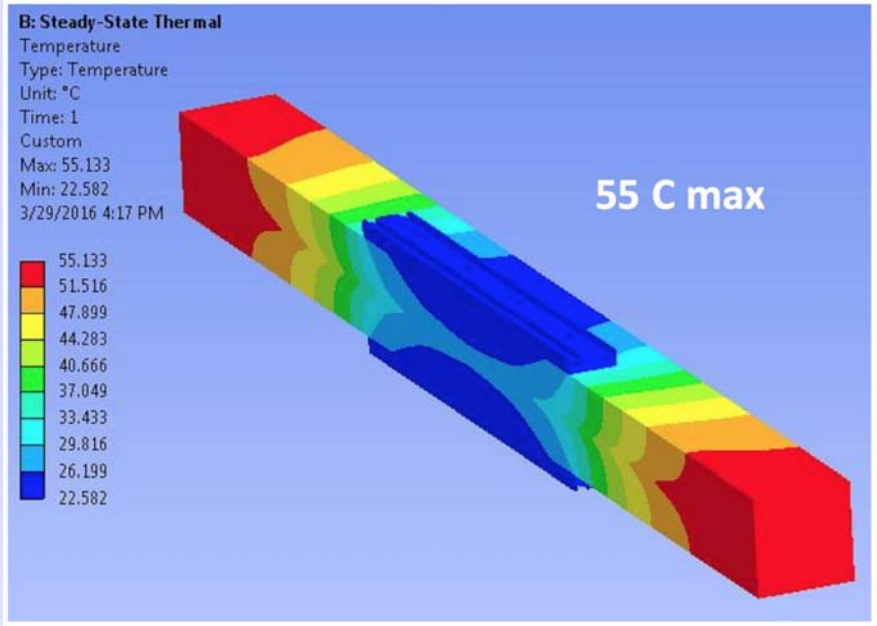
- Vibration: Improve design of channels and plenum
- *Is there enough cooling?*

Liquid-nitrogen cooling

- Just above LN_2, Si has zero thermal expansion
- *C adsorption?*
- *Shape change?*

Thermal modeling





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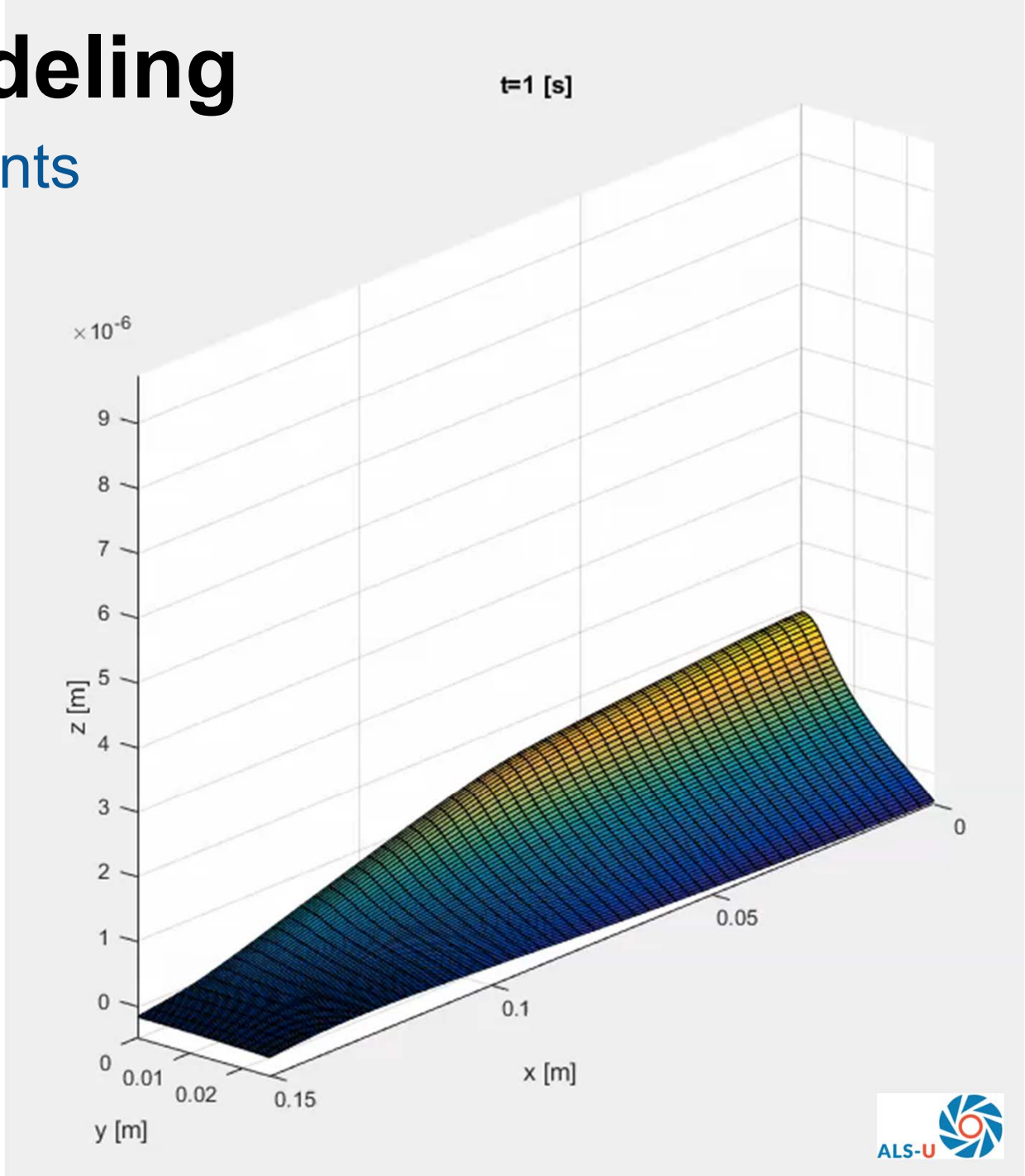
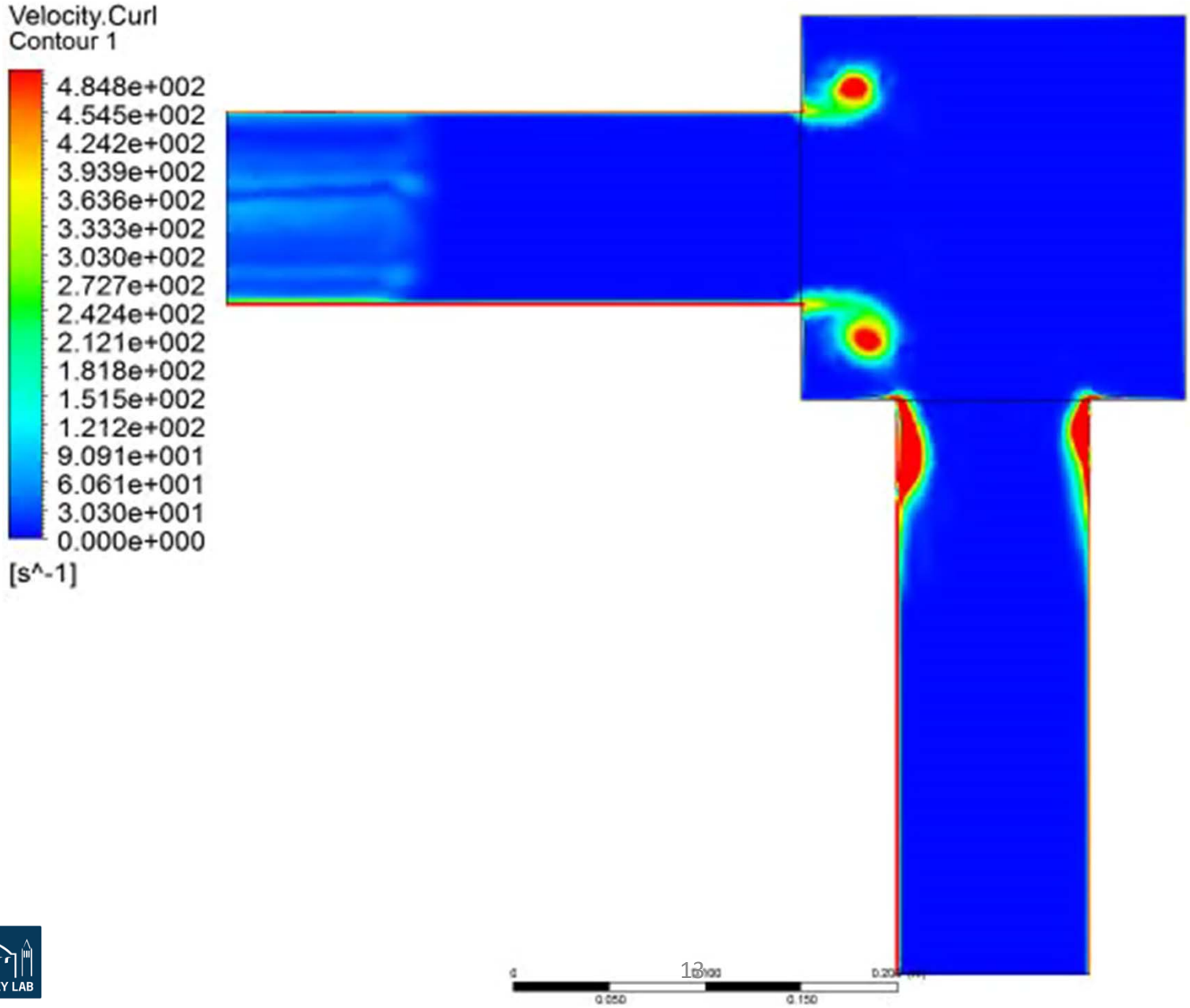
Thermal modeling

predict time constants
and vibration

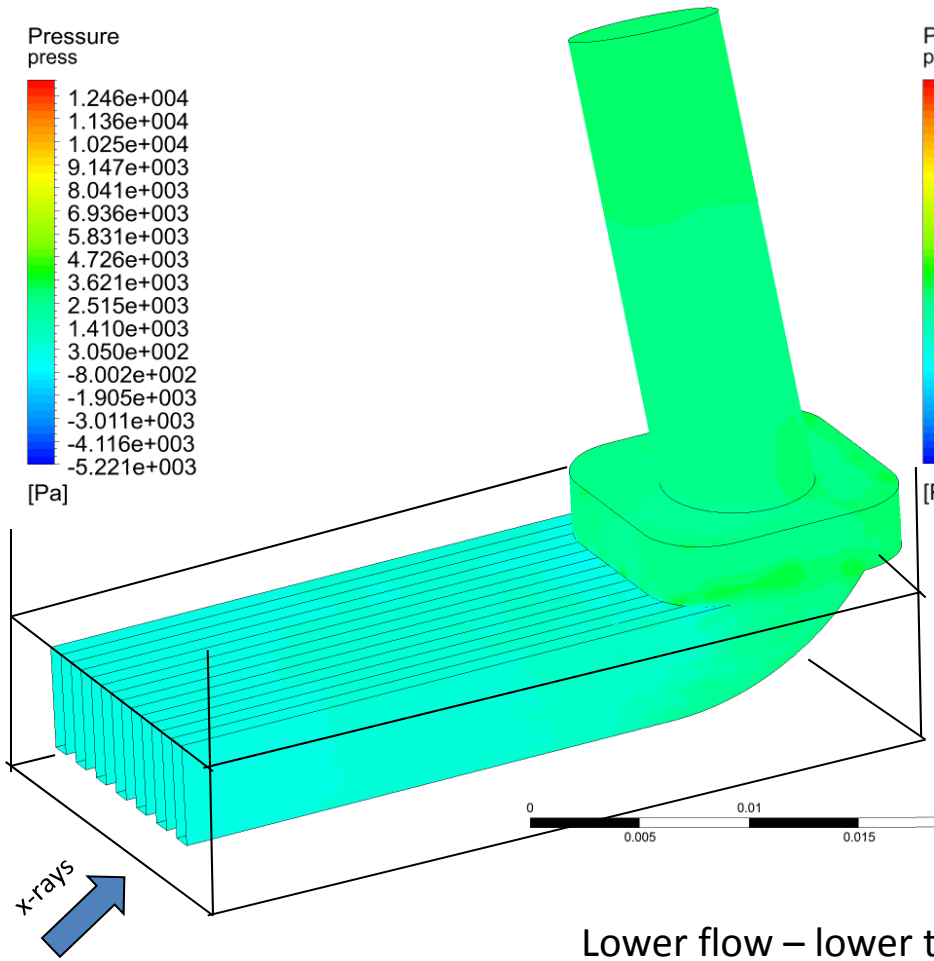


Test model for turbulent flow

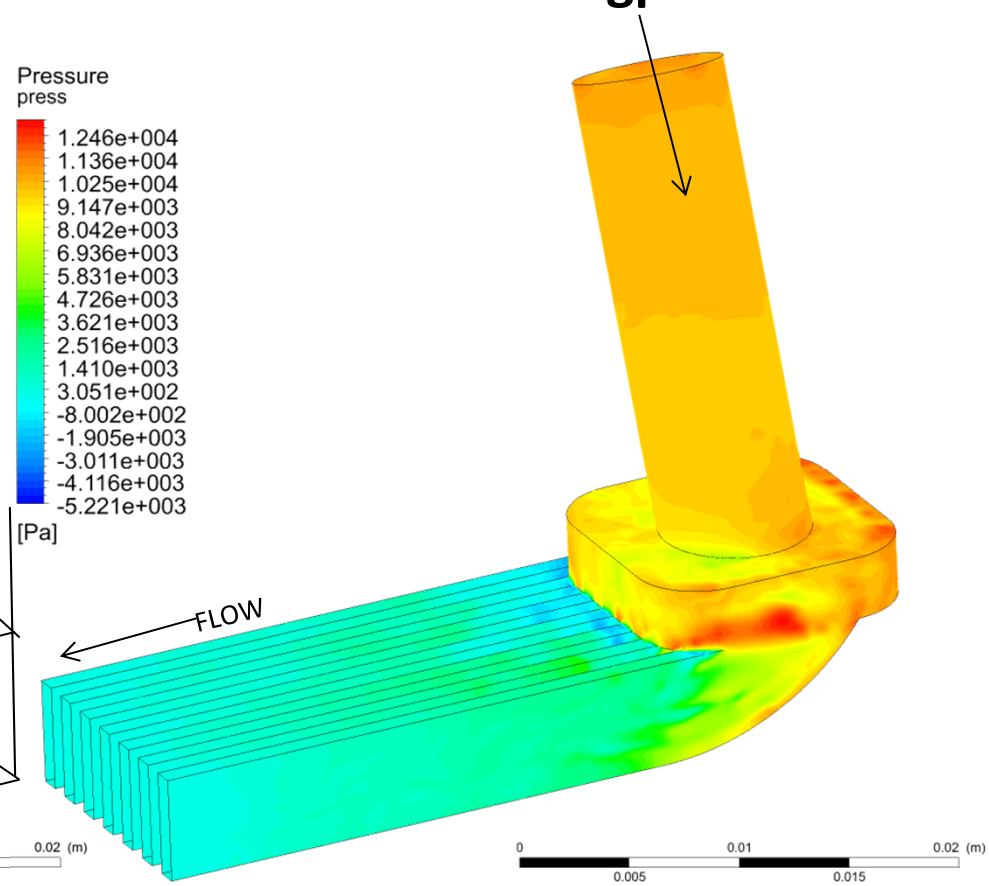


Calculated pressure distribution for two different flow rates

total flow rate = 0.75 gpm



total flow rate = 1.50 gpm



Lower flow – lower turbulence

Relative pressure to the reference pressure (taken as the discharge one at the outlet which is always at 0 Pa)

Vibration & mechanical stability

- beamline stands & supports
- internal mirror mounts
- active and passive isolation
- acoustics & environment
- beam-position monitors

Future X-ray optics—major concerns

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- carbon prevention / mitigation

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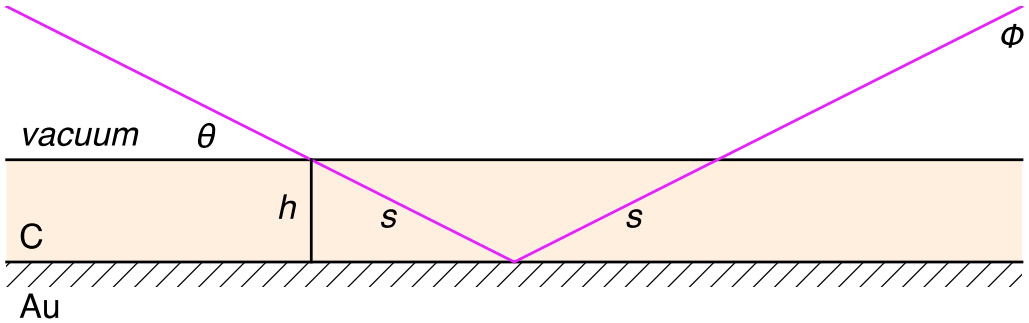
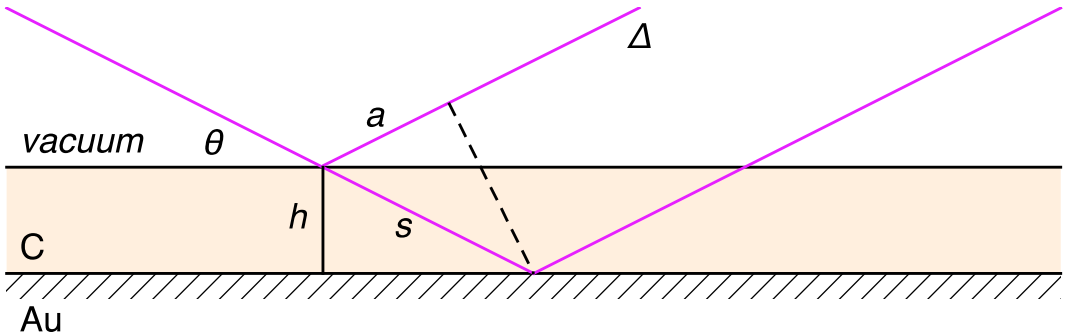
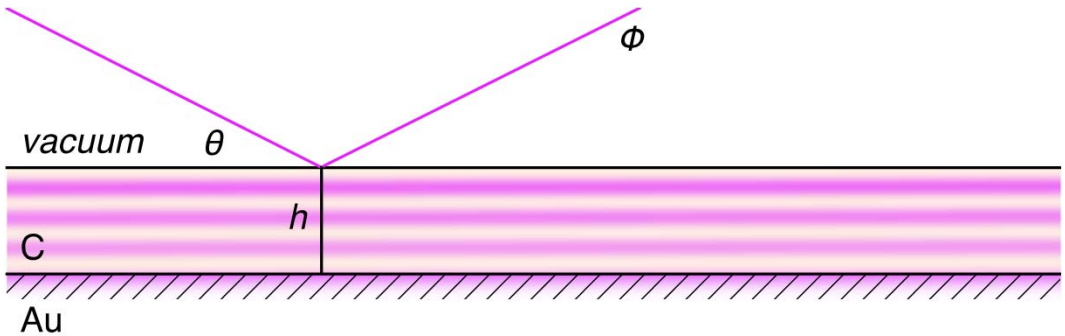
How to think about carbon



Phase-Only Model
(any wavefront error)
$\Delta \sim 2h\delta_C/\theta$



Geometric Model
(any wavefront error)
$\Delta = 2\theta h \rightarrow h \approx \lambda$



Wave Model
accounts for δ, β, *h*

nanometers matter

Preventing carbon contamination

- ***In situ* cleaning:** Can we adequately remove C using reactive plasmas?
- **LN_2**: Can we LN_2-cool optics w/o C adsorption?
- **Baking:** How hot must we bake optics to get good UHV?
- **Baking & LN_2 cooling:** Can we create optics that do not change shape with temperature?

Future X-ray optics—major concerns

- state-of-the-art surface profiles
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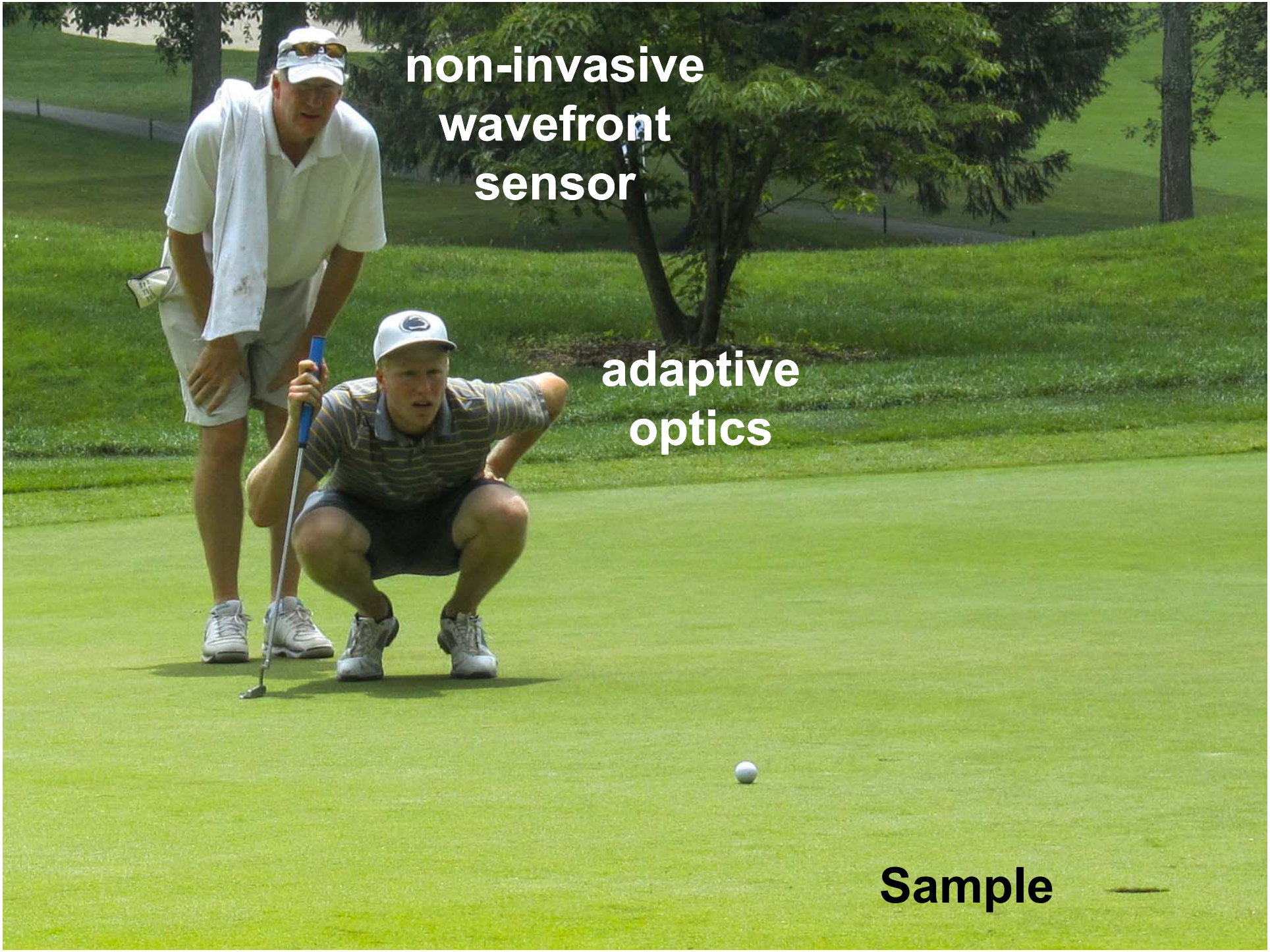
insertion device
Diffraction-Limited Light Source
endstation
beamline
hv


non-invasive
wavefront
sensor
adaptive
optics
Sample

Future X-ray optics

- state-of-the-art surface profiles
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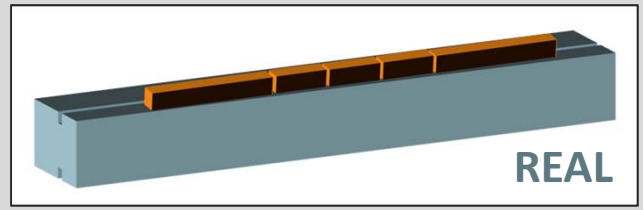
Invasive

Non-Invasive

Wavefront Preserving Mirrors Project

- Work with SLAC on the ***REAL*** mirror
- Project Funded by DOE
- Collaboration: **ALS • LCLS • NSLS-II • APS**

Goldberg • Cocco • Assoufid • Idir

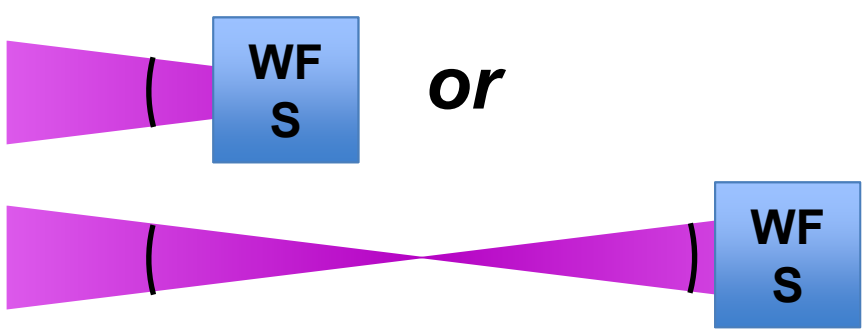


(Resistive Element Adjustable Length)

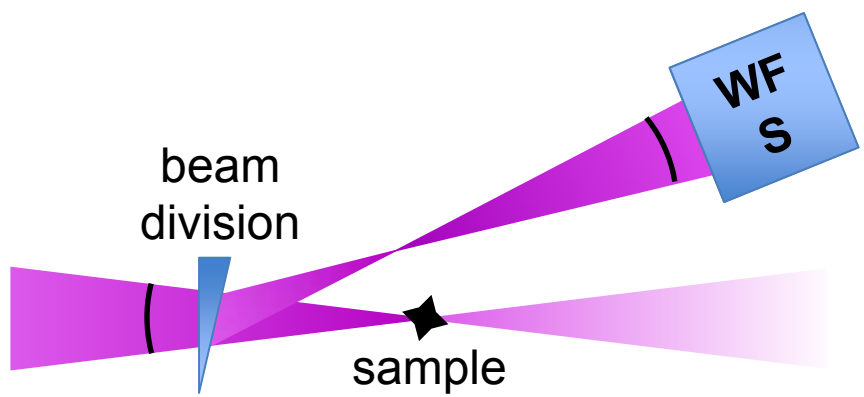
For ALS-U, the project includes:

- Development of an **<u>invasive</u> at-wavelength wavefront sensor**
- **Tests conducted on a beamline** at one of the facilities, possibly ALS
- Resarch *(only)* on a **non-invasive wavefront sensor**

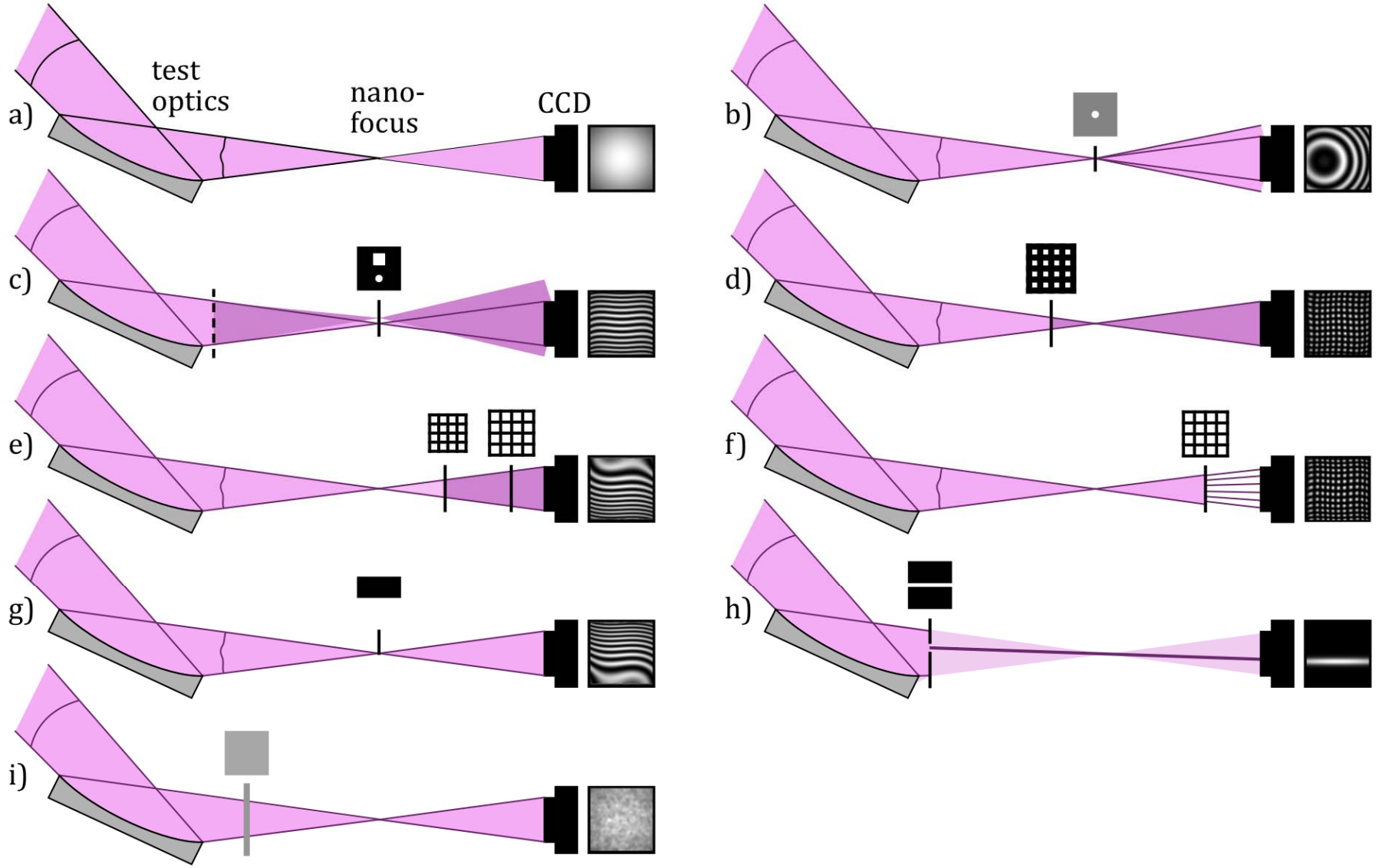
"Invasive"



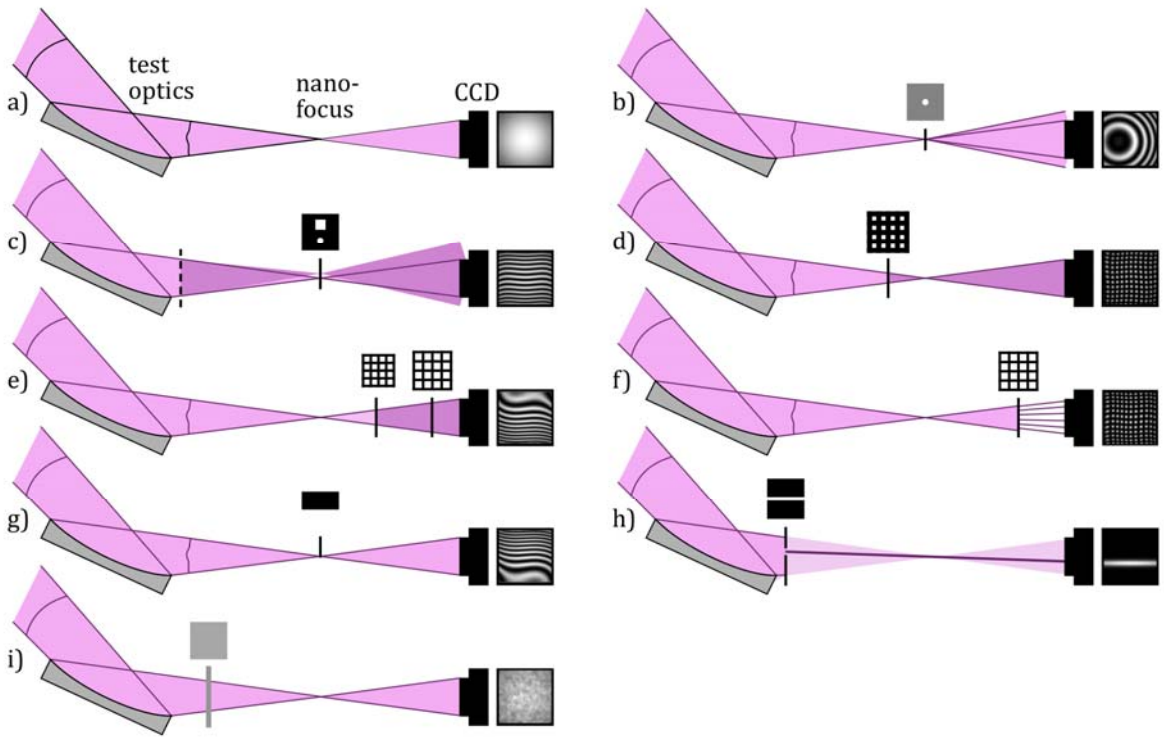
"Non-Invasive"



In-situ Wavefront Metrology Modes



In-situ Wavefront Metrology Modes



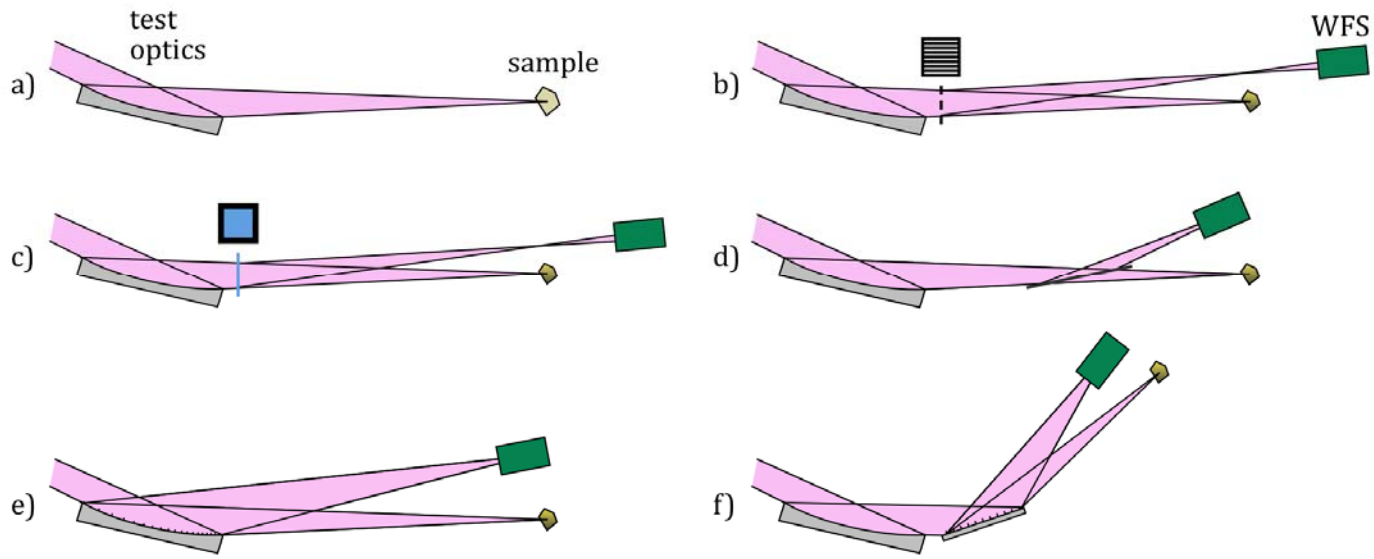
Many different approaches

Point-diffraction, Phase-shifting point-diffraction, Cross-grating lateral shearing, Talbot, Hartmann, Knife-edge, Scanning slit, Speckle interferometry.

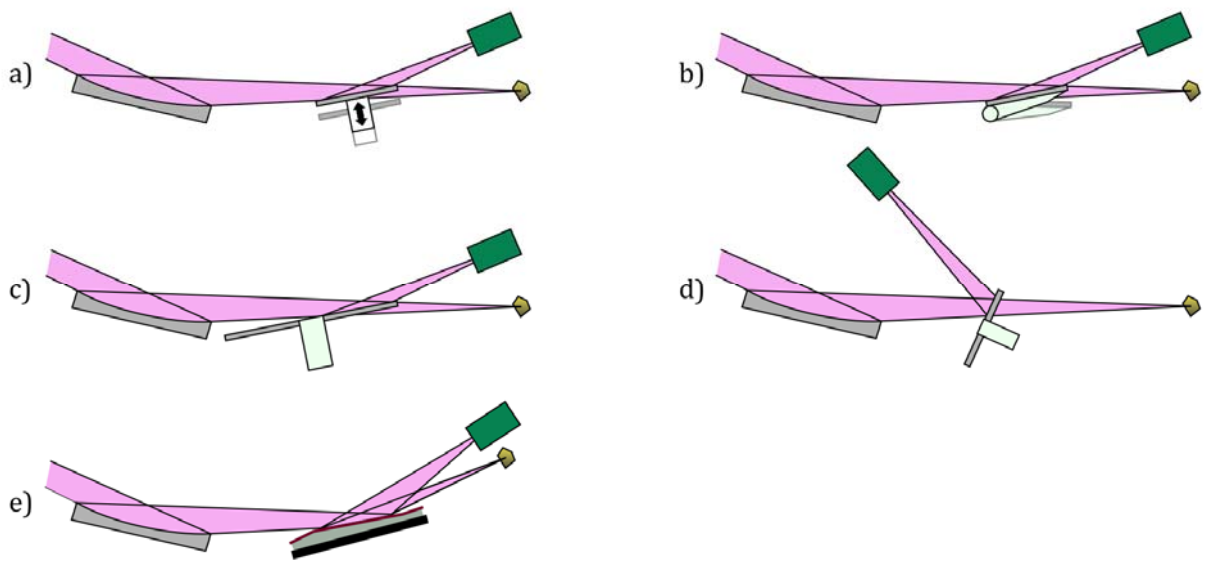
We will study *through modeling*

- suitability for different **beam energies**
- **sensitivity** vs. photon flux & design parameters
- **accuracy** vs. fabrication errors and and positioning tolerances
- **stability** and vibration tolerance
- **dynamic range** vs. design

Static and dynamic beam division modes for <u>non-invasive</u> metrology

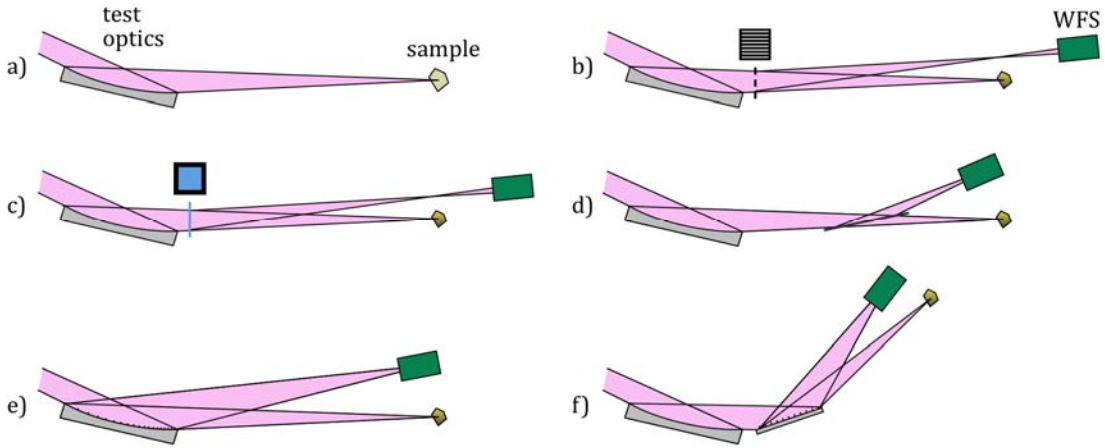


Static



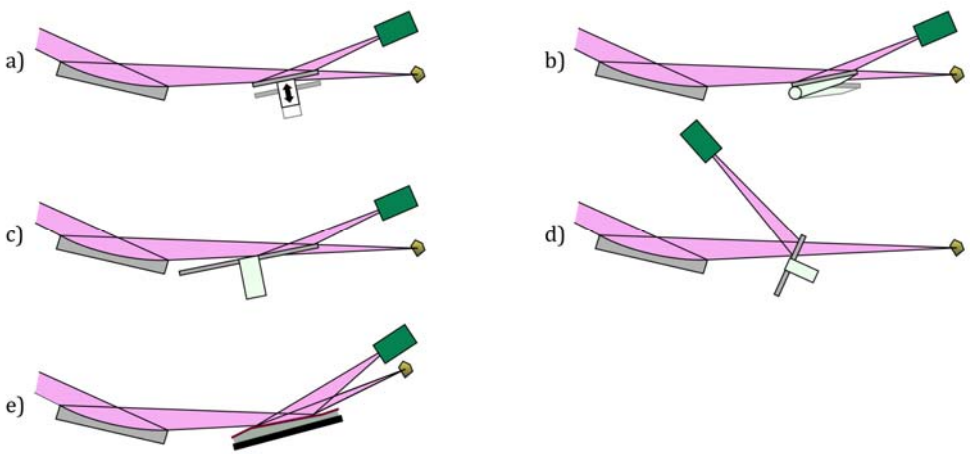
Dynamic

Static and dynamic beam division modes for <u>non-invasive</u> metrology



Static beam division

Transmission grating, crystal, thin film beam splitter, grating on a curved mirror surface, reflection grating



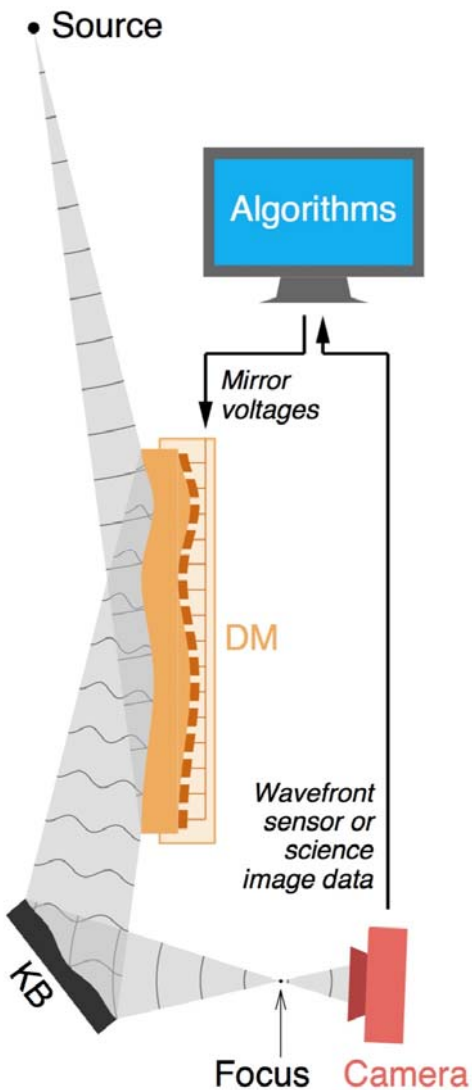
Dynamic beam division

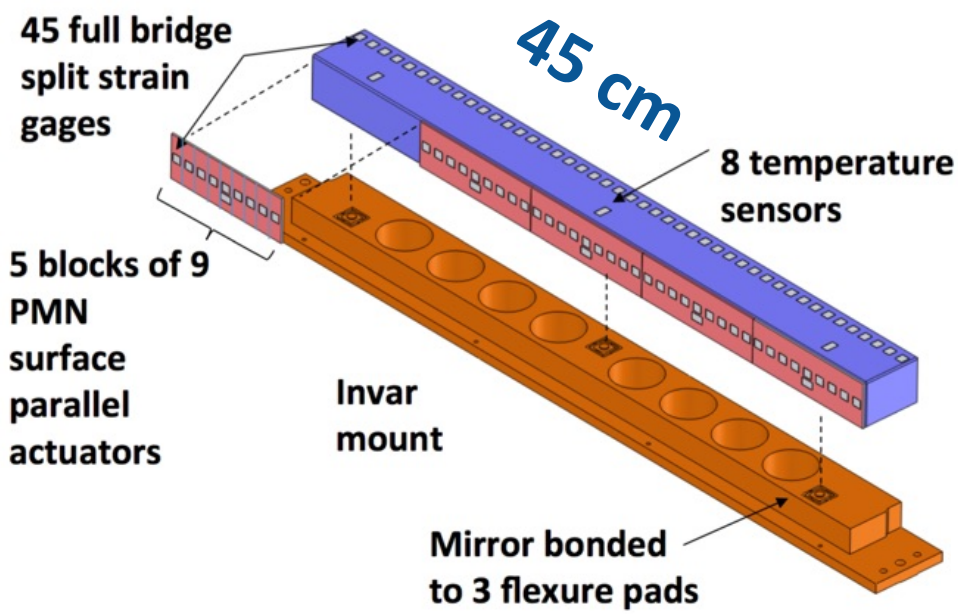
Piston-style mirror actuator, pivoting actuator, glancing-incidence rotating chopper, normal-incidence rotating chopper, high bandwidth adaptive mirror

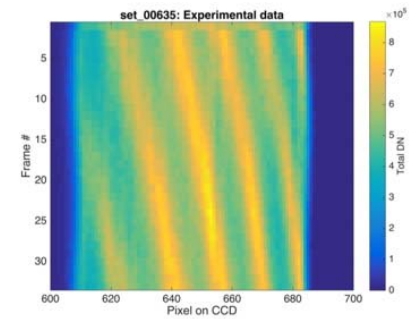
ALS-U needs non-invasive WFS as feedback for adaptive optics.
Static or dynamic beam-division will send a fraction of light into the WFS.
Innovation: ***Non-invasive metrology tools do not currently exist.***

Adaptive Optics Concepts

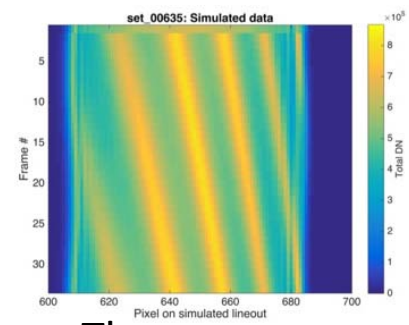
LLNL demonstration AXO tested at the ALS. [Poyneer, *et al.*]







Experiment



Theory

- LLNL team has AO telescope experience.
- Promising demonstrations of control and prediction at 3 keV.
- Large monolith; 45 actuators; high speed; nm-scale control.
- LLNL team is looking to continue their work, and help on ALS-U.

ALS-U will need: *more compact device; UHV; 2D control.*

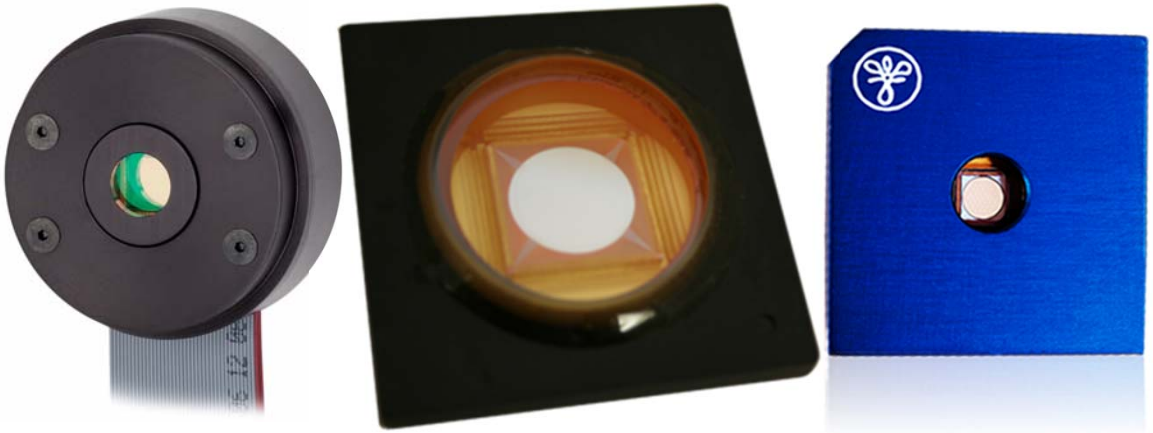
Adaptive Optics Concepts

Commercial *visible-light* systems from several vendors

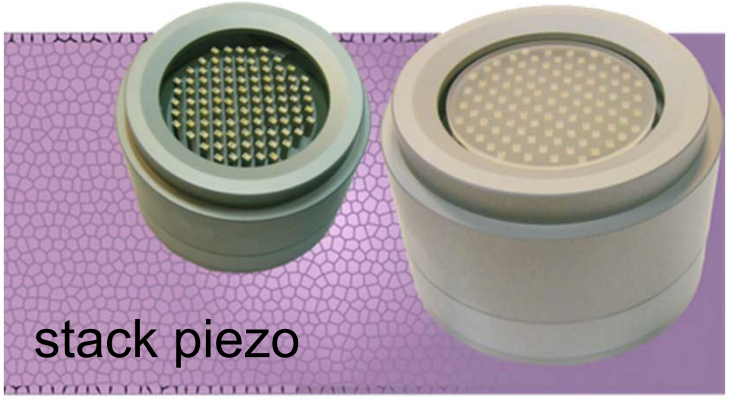
AKA Optics

Boston Micromachines Corporation

Iris AO



MEMS-based deformable membranes



We will evaluate current technologies to see what techniques can be *adapted* to soft x-ray

- glancing incidence
- sub-nm control
- UHV
- compatible coating
- low roughness

Development of Robust Adaptive Optics Systems and Wavefront Sensors

The REAL mirror project takes us just a few steps toward where we need to go.

Wavefront Preserving Mirrors Project (2 yrs) → **ALS-U Research** *Critical R&D* → ***Continued Development***

invasive WFS → non-invasive WFS → adaptive optics → beam drift comp. → high speed → beam profile

REAL mirror

Modeling WFSs

Create invasive WFS

Research non-invasive WFS

Create/test beam dividers for various wavelengths

Create/test non-invasive WFS

Research Adaptive Optics (AO) for various wavelengths

Create & test AO devices

Fast WFS + AO
→ vibration compensation

Target higher speed & tigher WF specs.

WFS + AO for beam stability/vibration comp.

Create AO with higher spatial frequencies and higher dynamic range.

Beam intensity-profile control.

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Goldberg

MacDowell

Padmore

Allézy

Cutler

Yashchuk

Feng

Miyakawa

Nasiatka