# At-wavelength Interferometric KB Mirror Alignment and Optimization

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# VOTE

- [ ] "Coherence Preserving"
- [x] "Wavefront Preserving"

# At-wavelength Interferometric KB Mirror Alignment and Optimization

**Goal:** Soft x-ray **nanofocusing**
*and methodology*

**Strategy:** Investigate various methods of wavefront metrology

**Approach:** *In situ at-wavelength* optimization

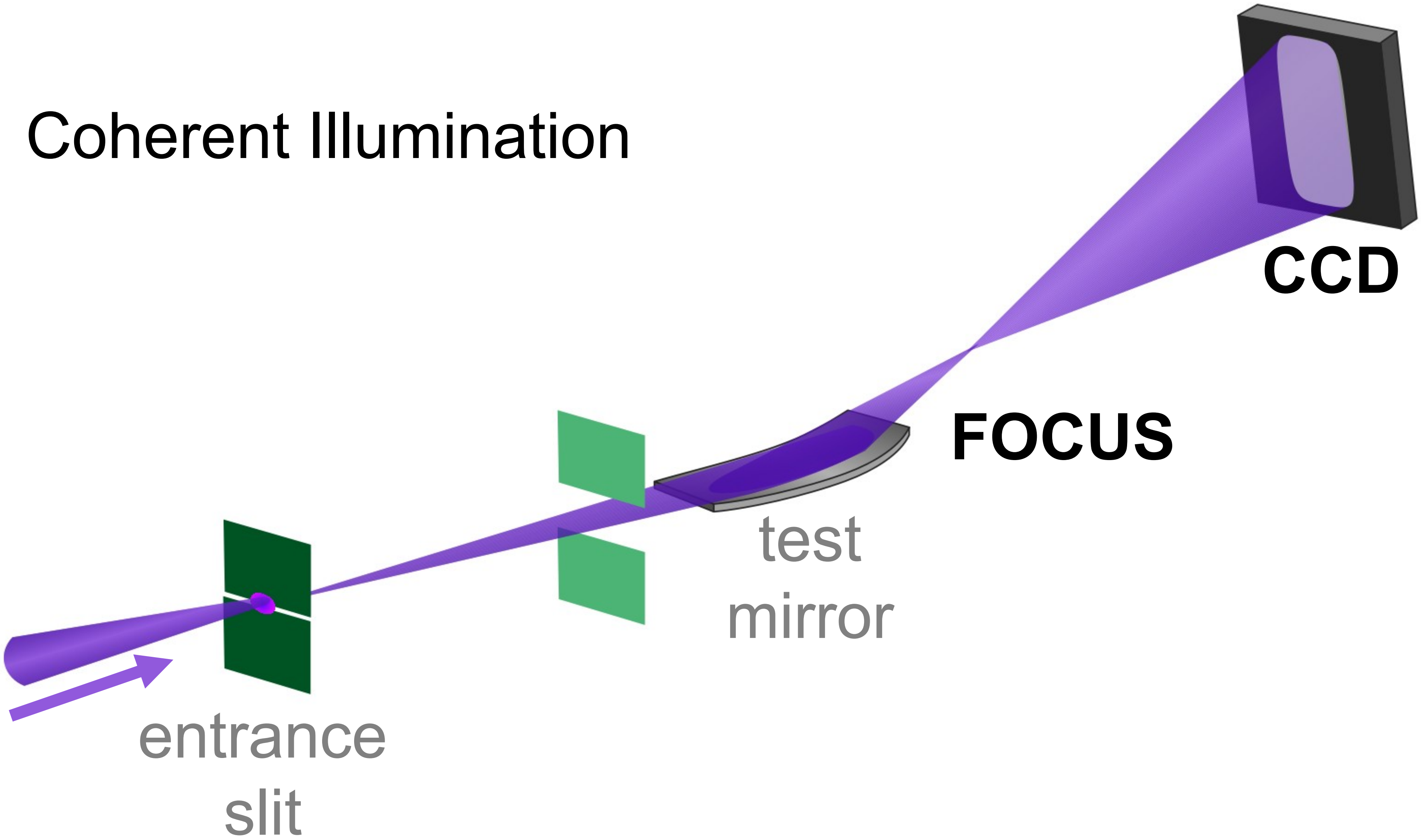
Inter-comparison

Correlation with visible LTP

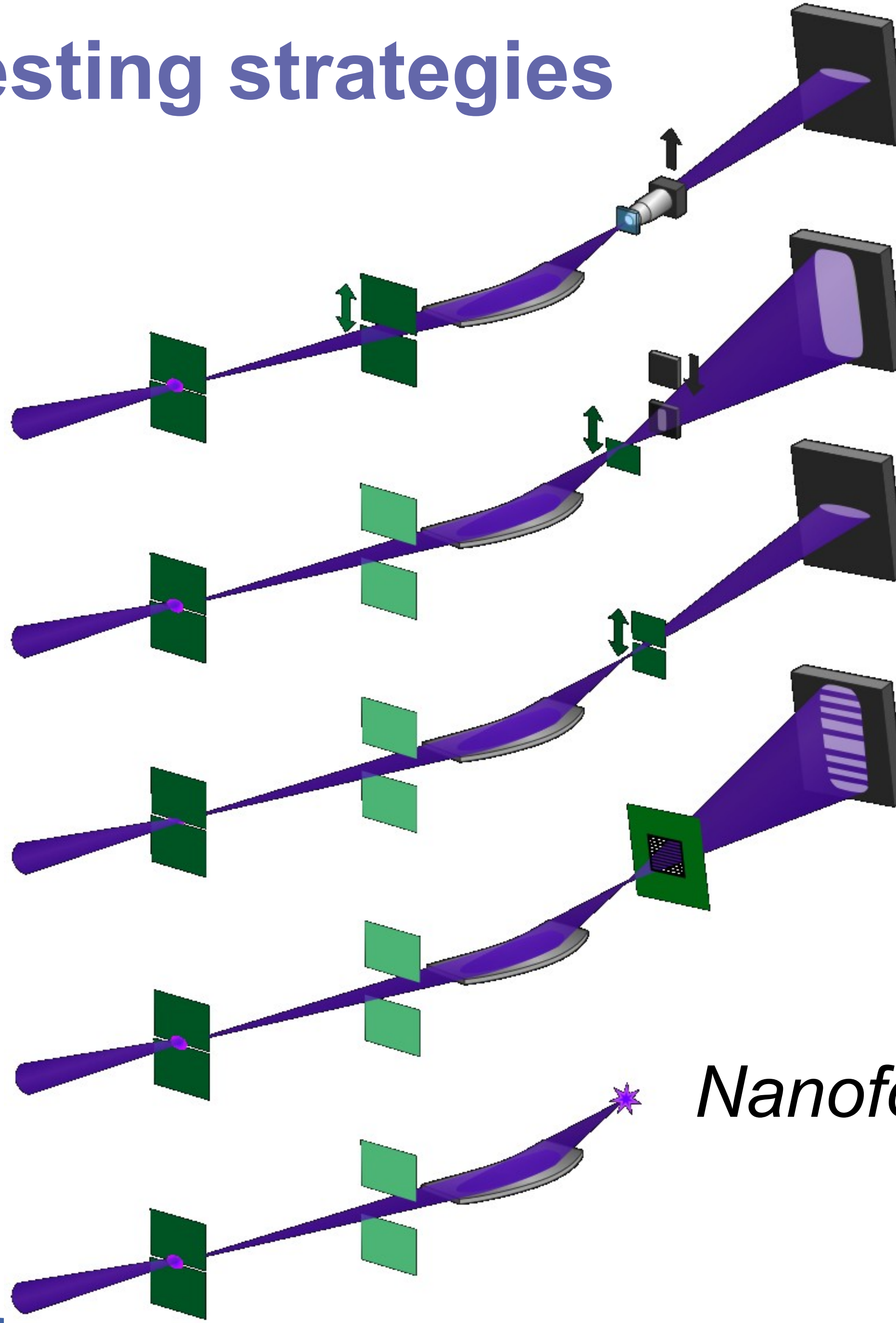
Test and **transfer**

# At-wavelength testing strategies

Coherent Illumination



# At-wavelength testing strategies



(Upstream)
Scanning Slit

Knife-Edge
(Foucault)

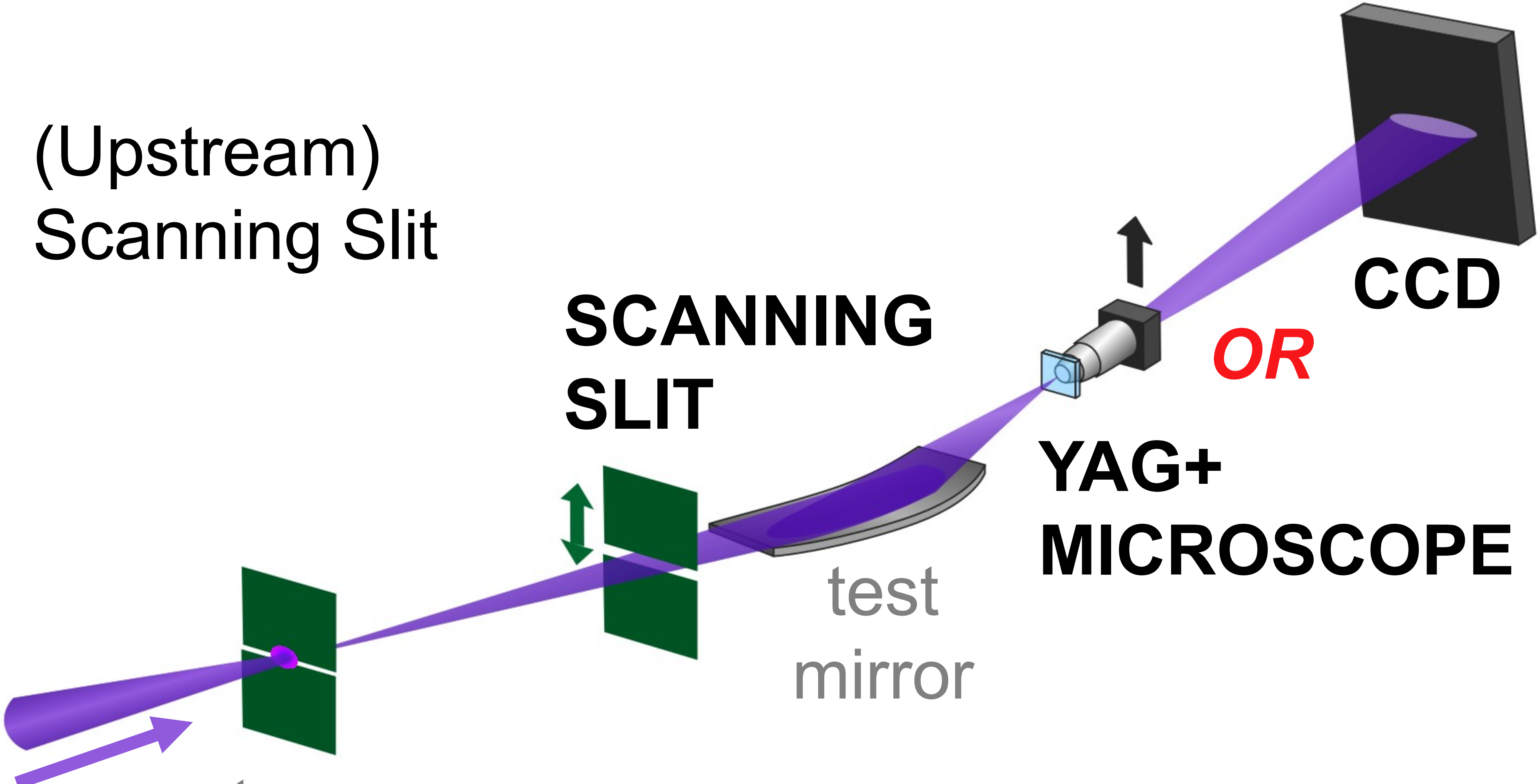
(Downstream)
Scanning Slit

Grating-Based
Lateral Shearing

*Nanofousing!*

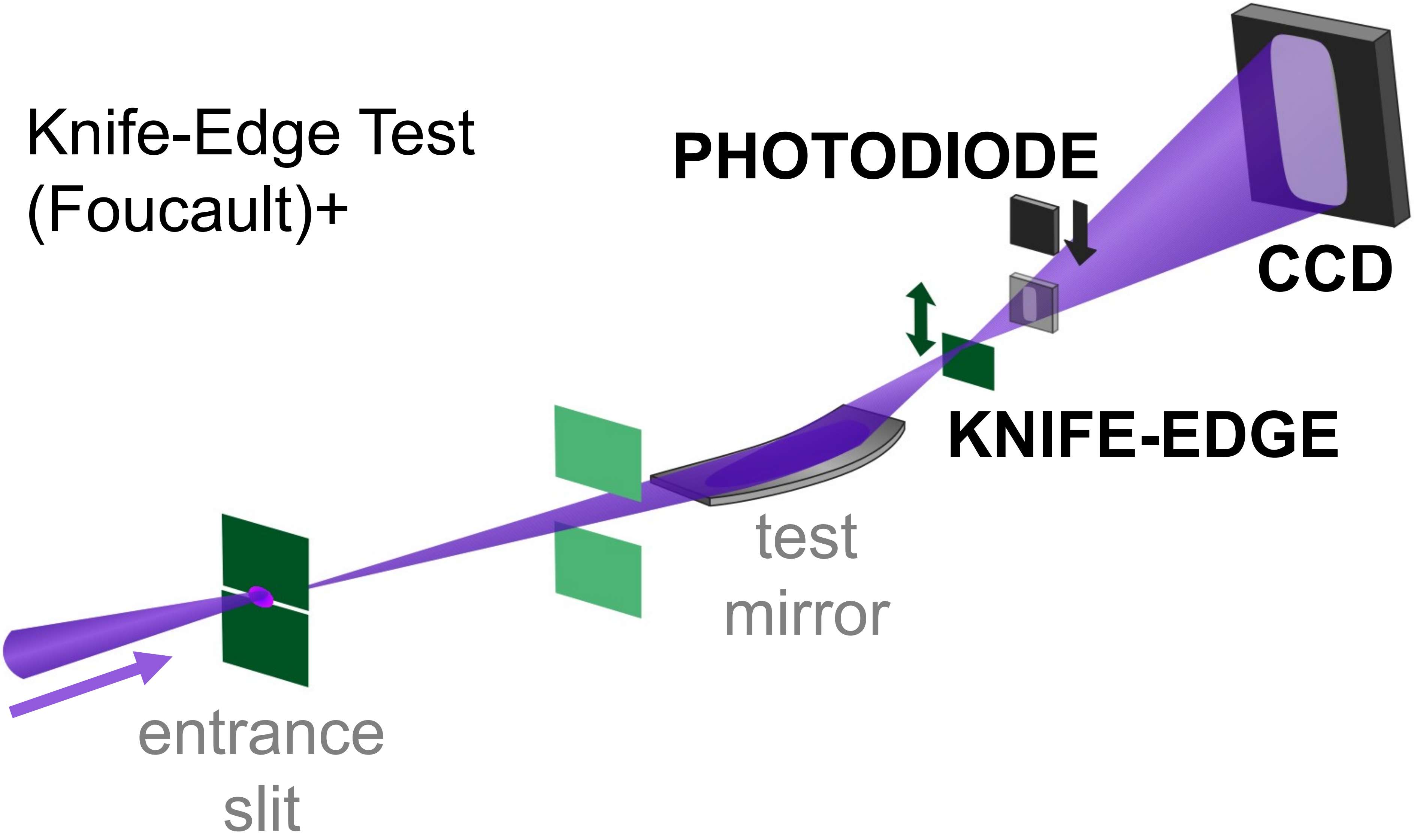
# At-wavelength testing strategies

(Upstream)
Scanning Slit



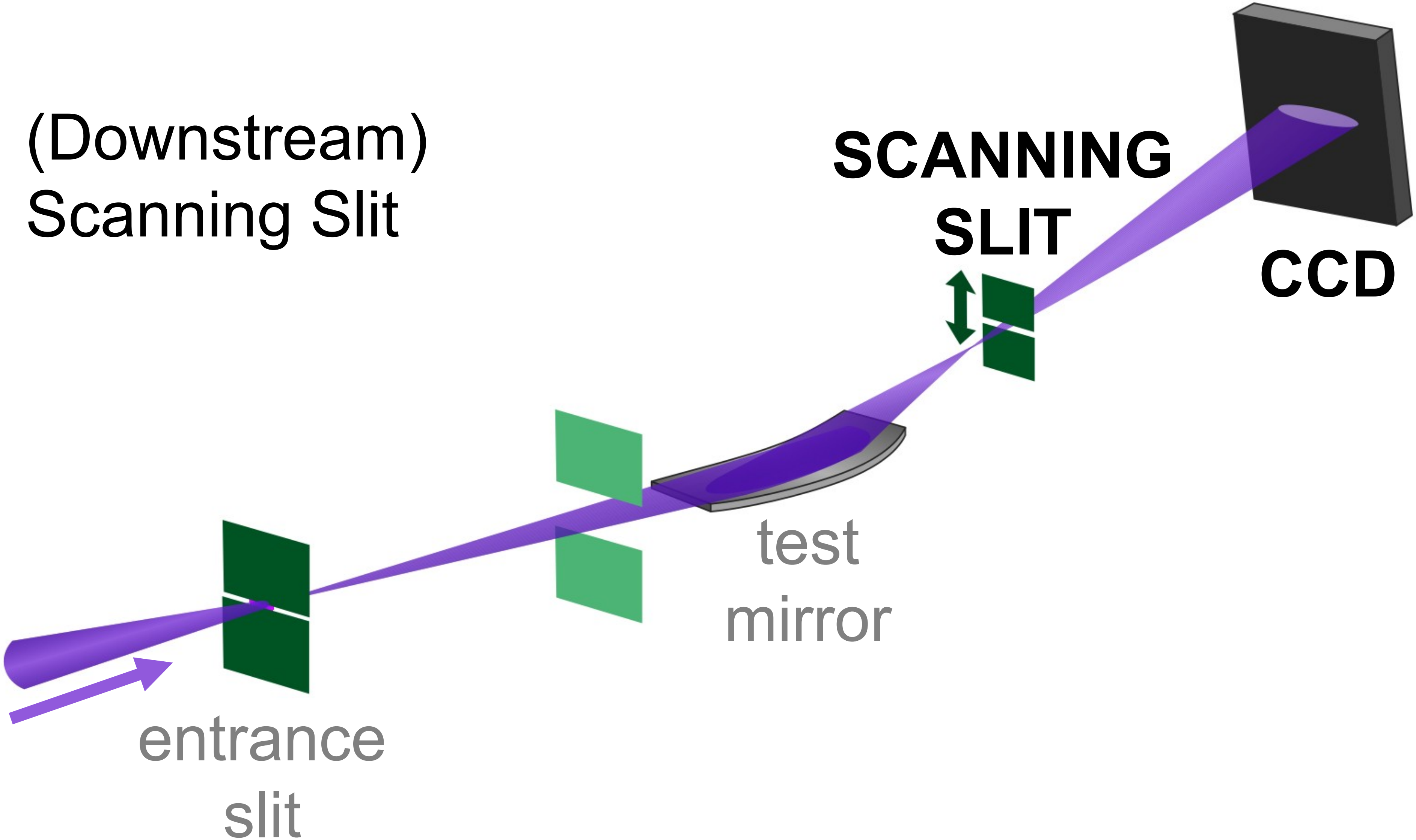
# At-wavelength testing strategies

Knife-Edge Test
(Foucault)+



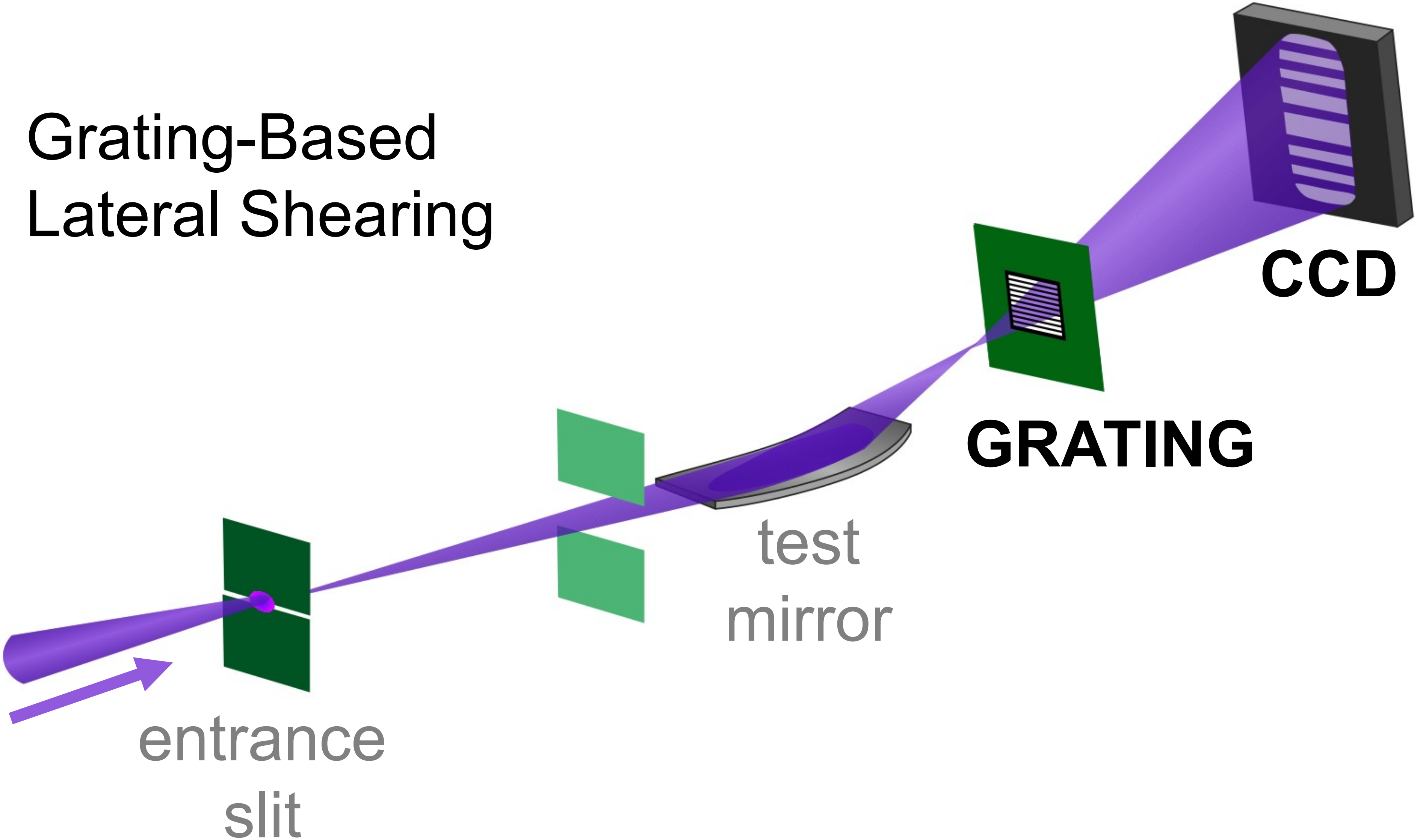
# At-wavelength testing strategies

(Downstream)
Scanning Slit



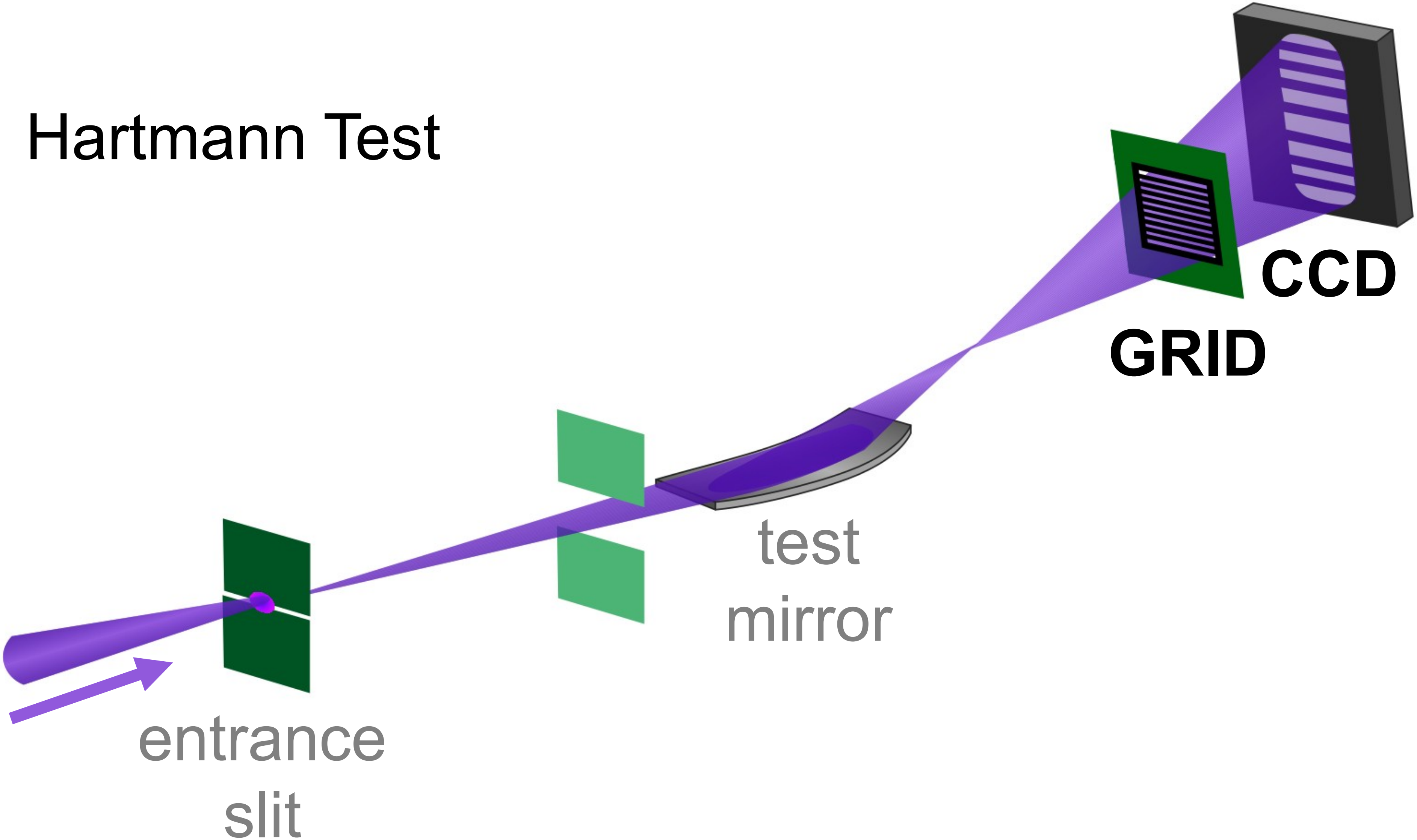
# At-wavelength testing strategies

Grating-Based
Lateral Shearing

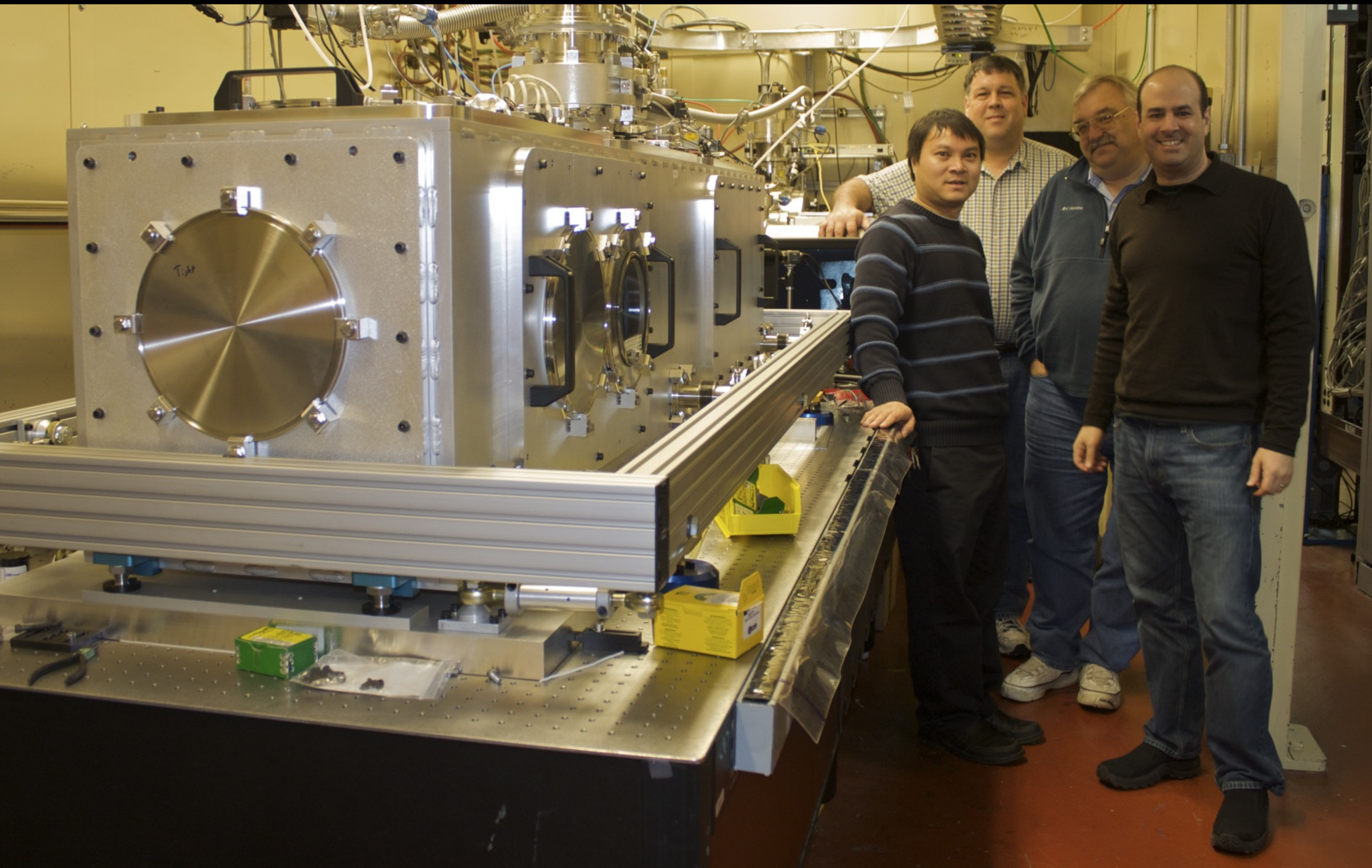


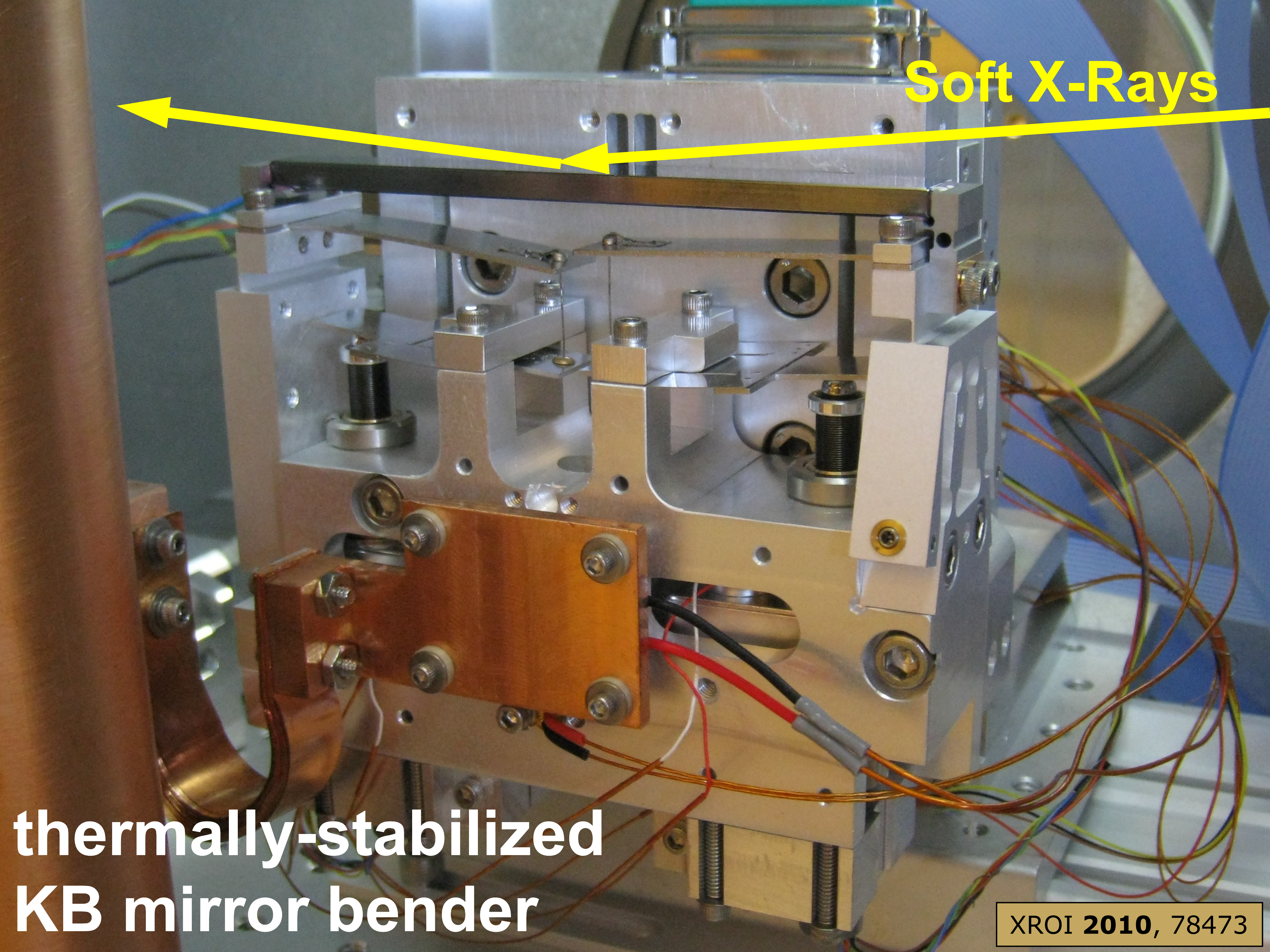
# At-wavelength testing strategies

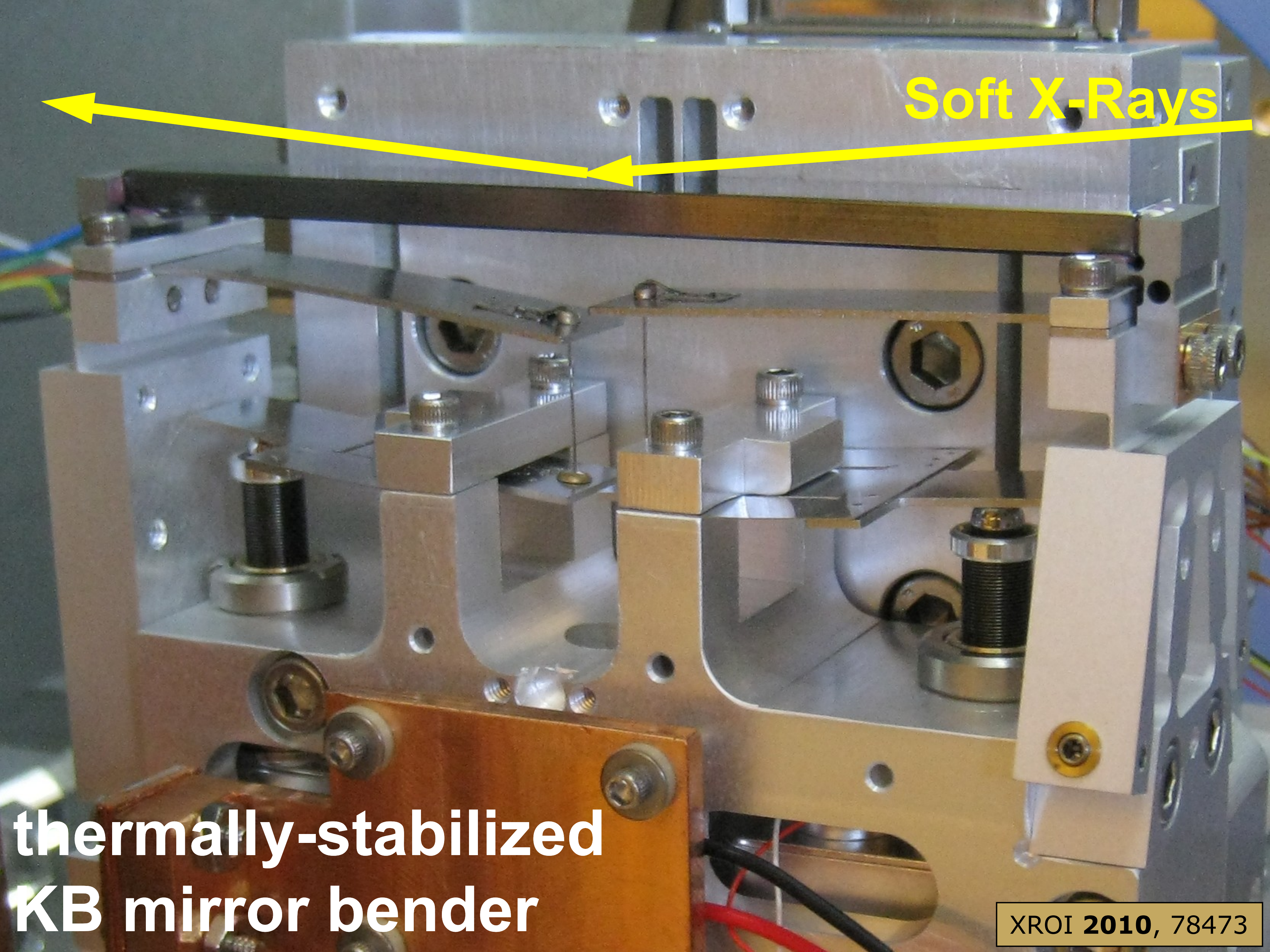
Hartmann Test



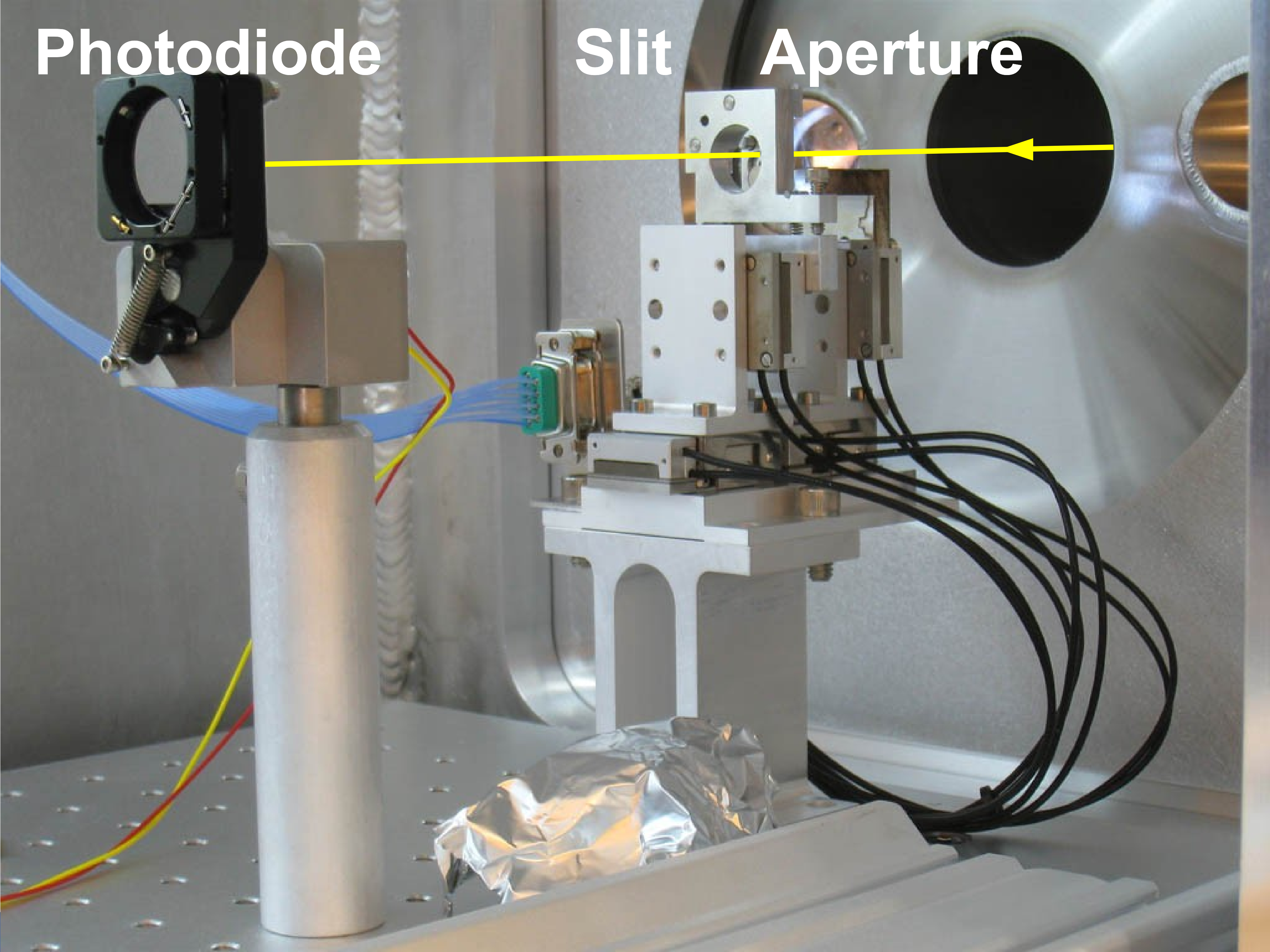
# Yuan, Celestre, Yashchuk, Goldberg
## **ALS Metrology Beamline 5.3.1**

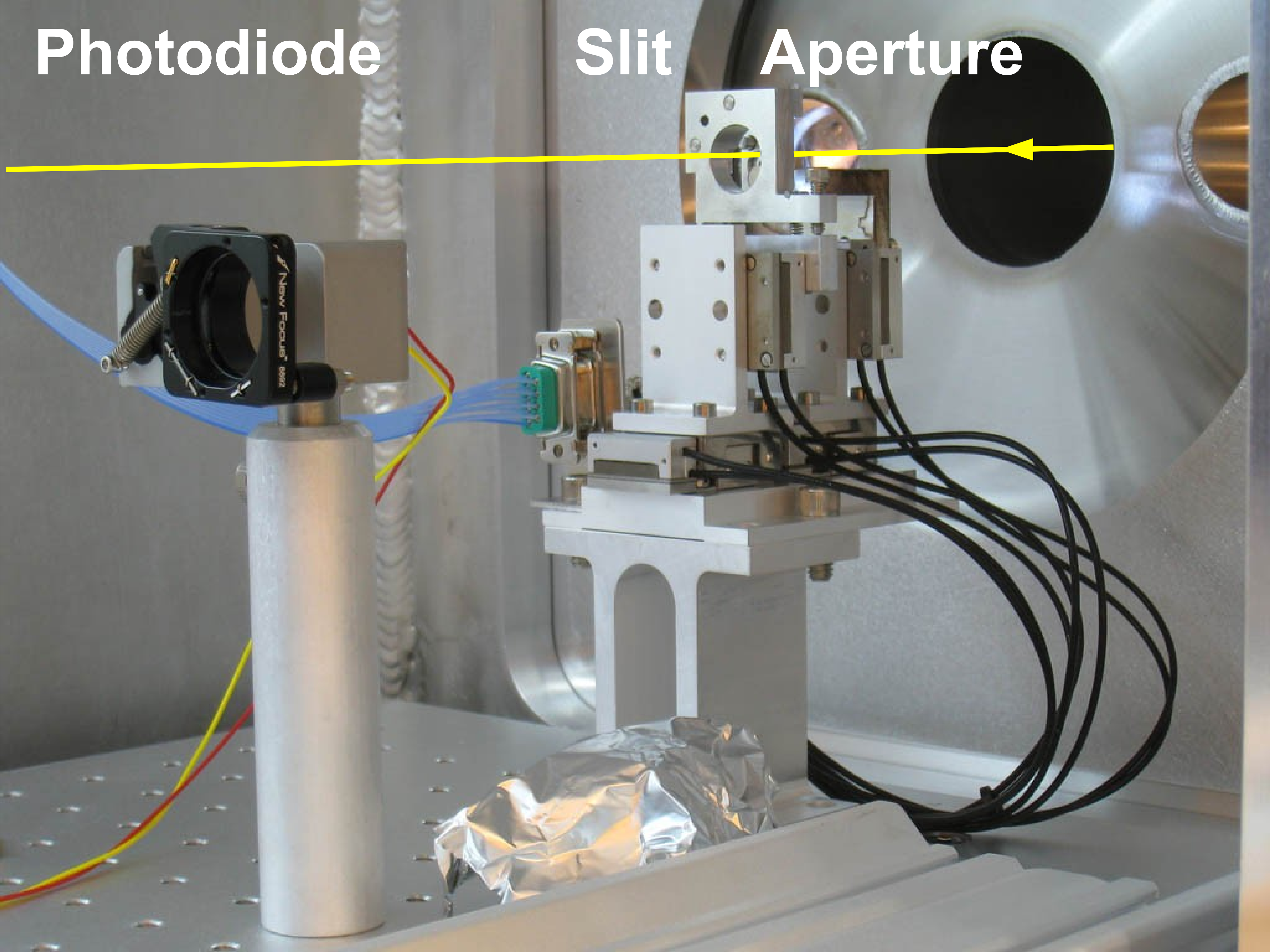


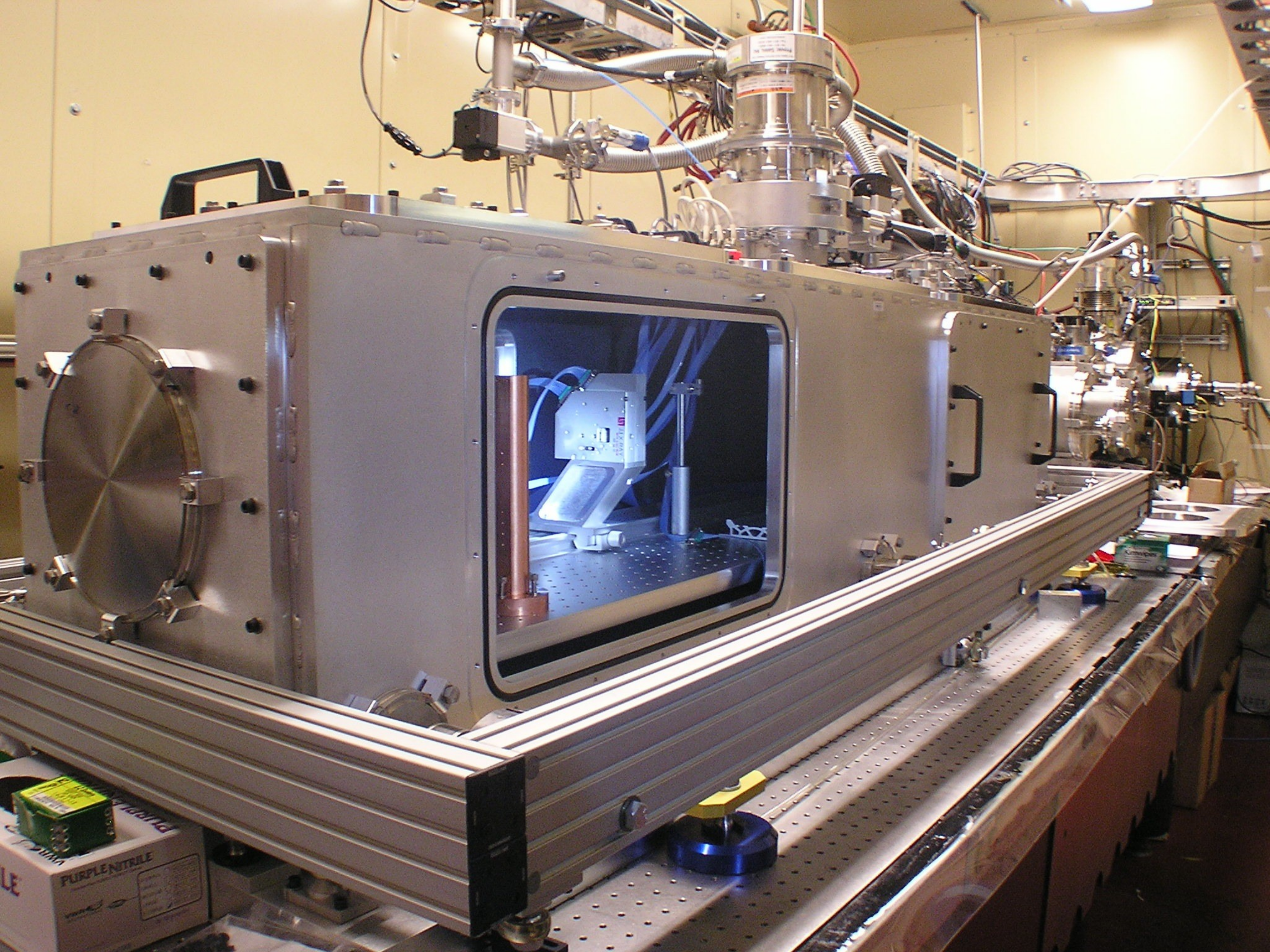

Soft X-Rays
thermally-stabilized
KB mirror bender
XROI 2010, 78473

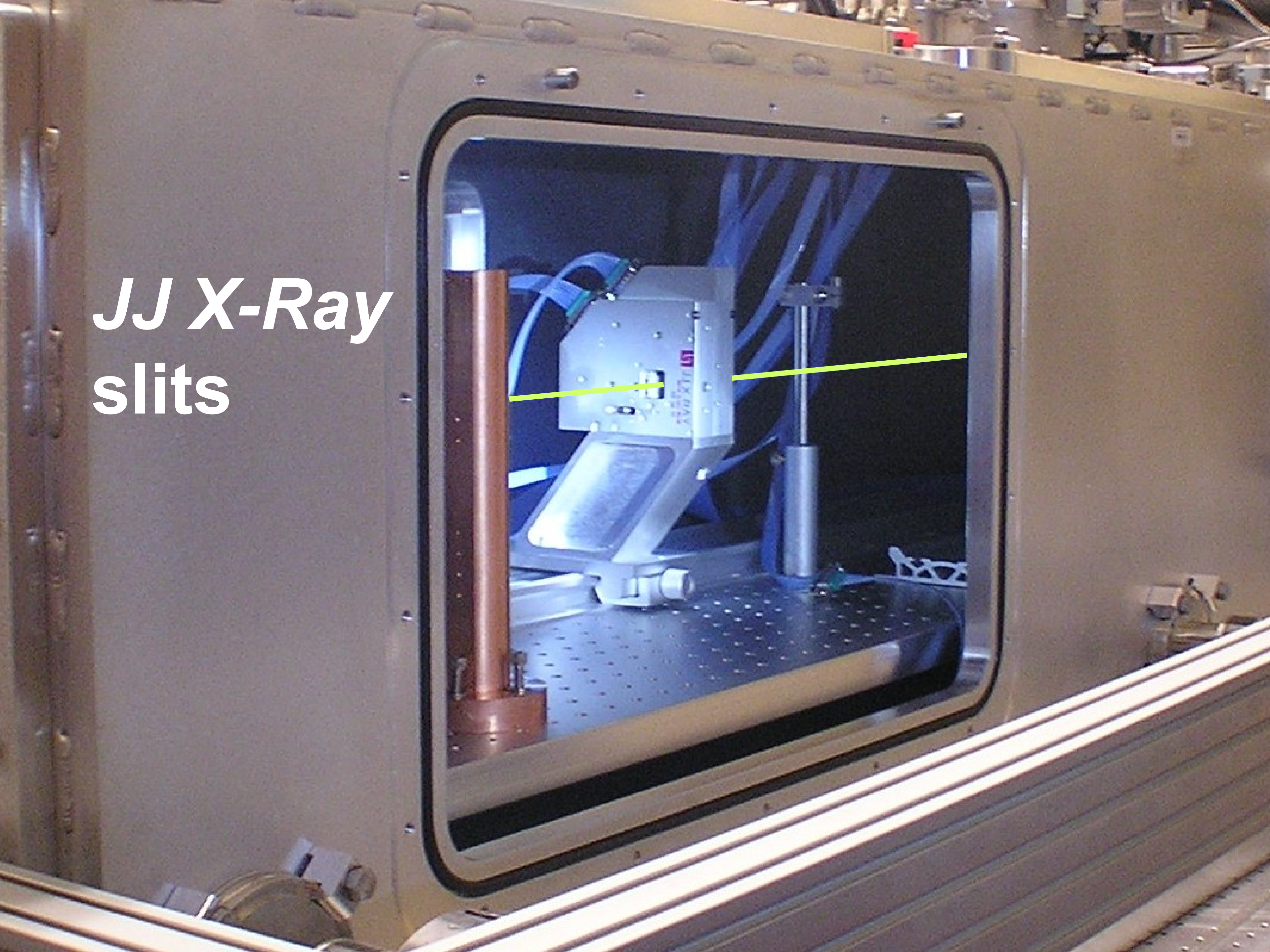

Soft X-Rays
thermally-stabilized
KB mirror bender
XROI **2010**, 78473

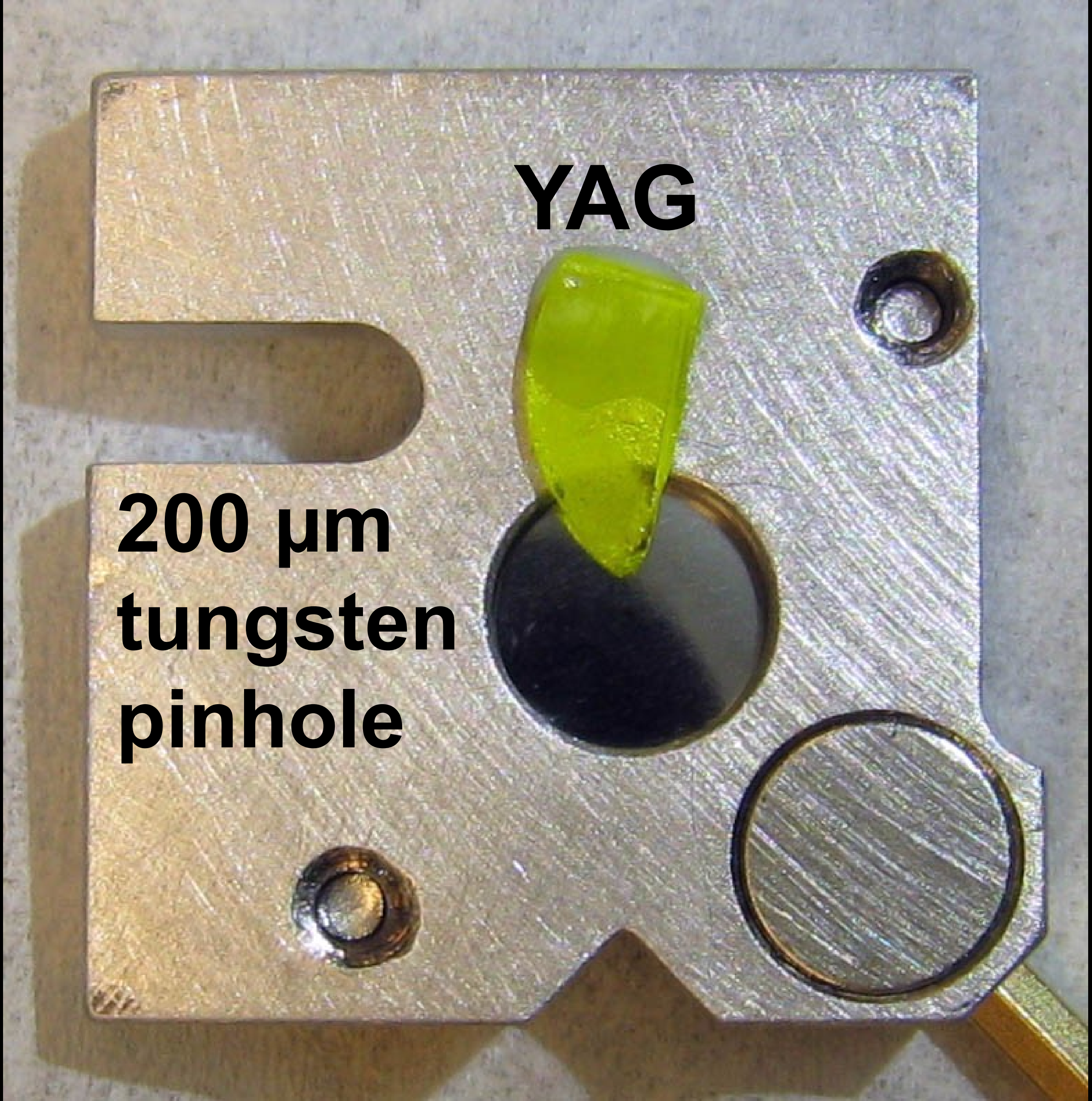

beam
Morrison


Photodiode
Slit
Aperture


Photodiode
Slit
Aperture
New Focus

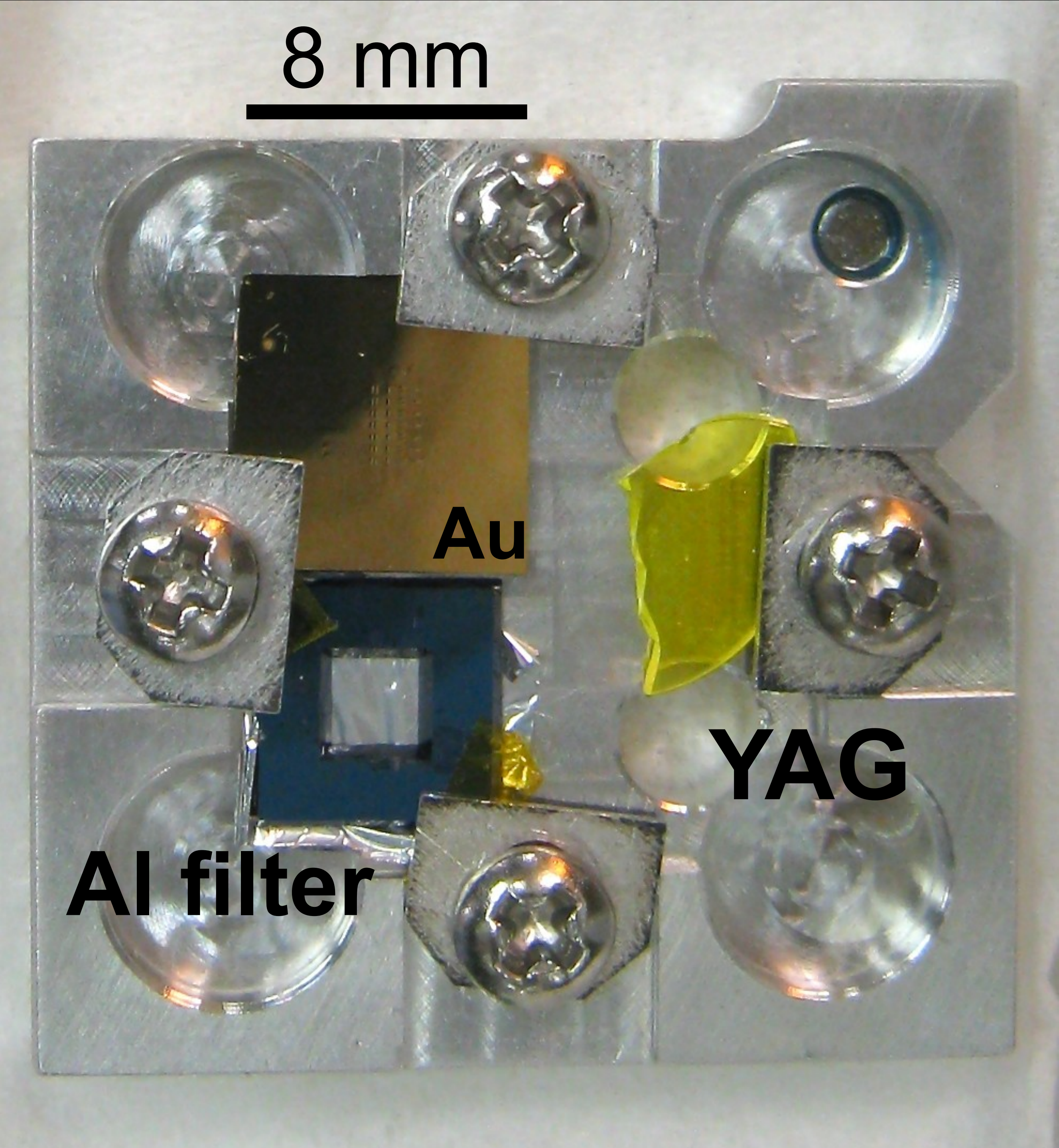

PURPLE NITRILE


JJ X-Ray
slits


YAG
200 µm tungsten pinhole

# object-side nanostructures

8-mm chip
2-mm window



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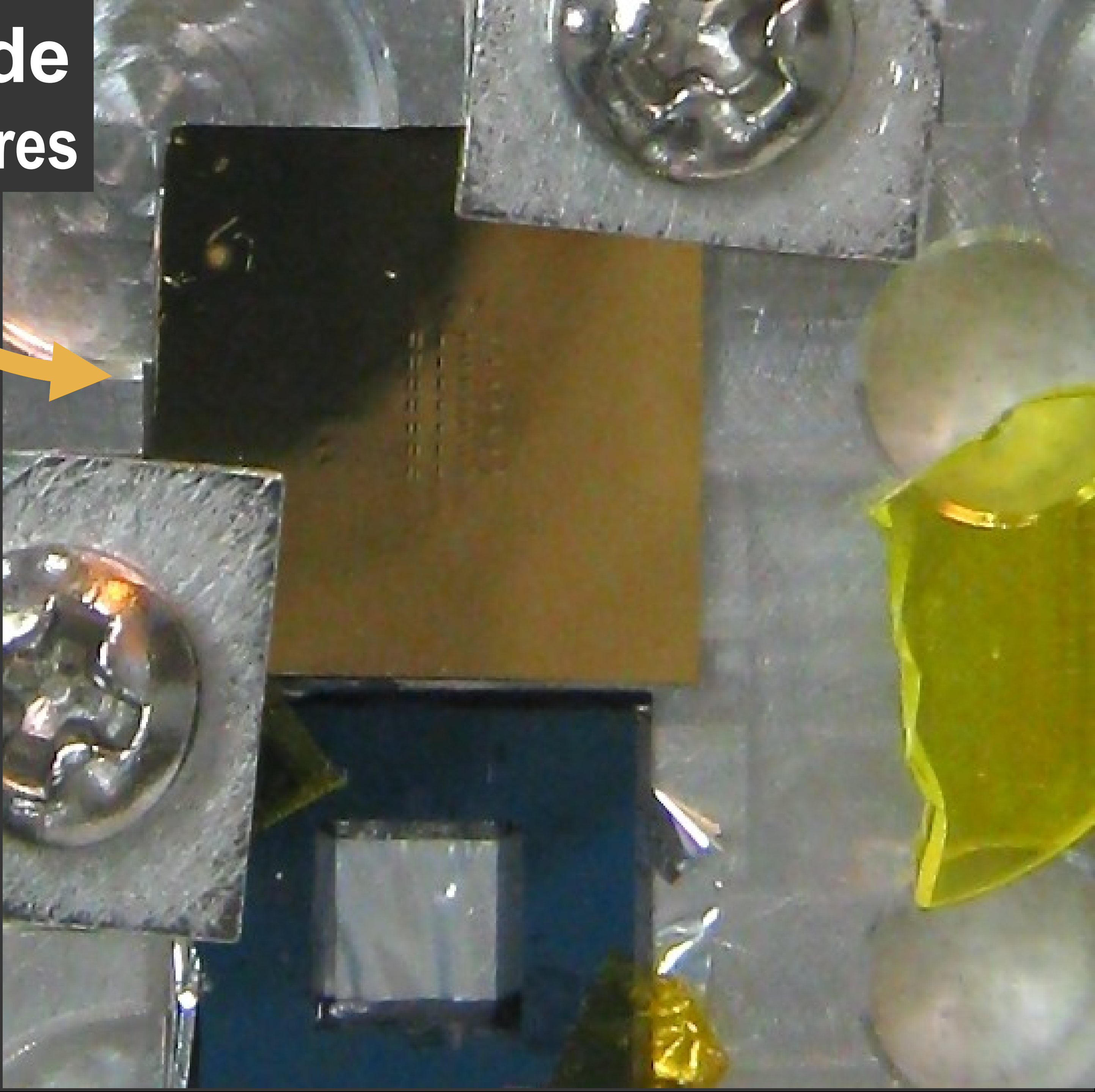
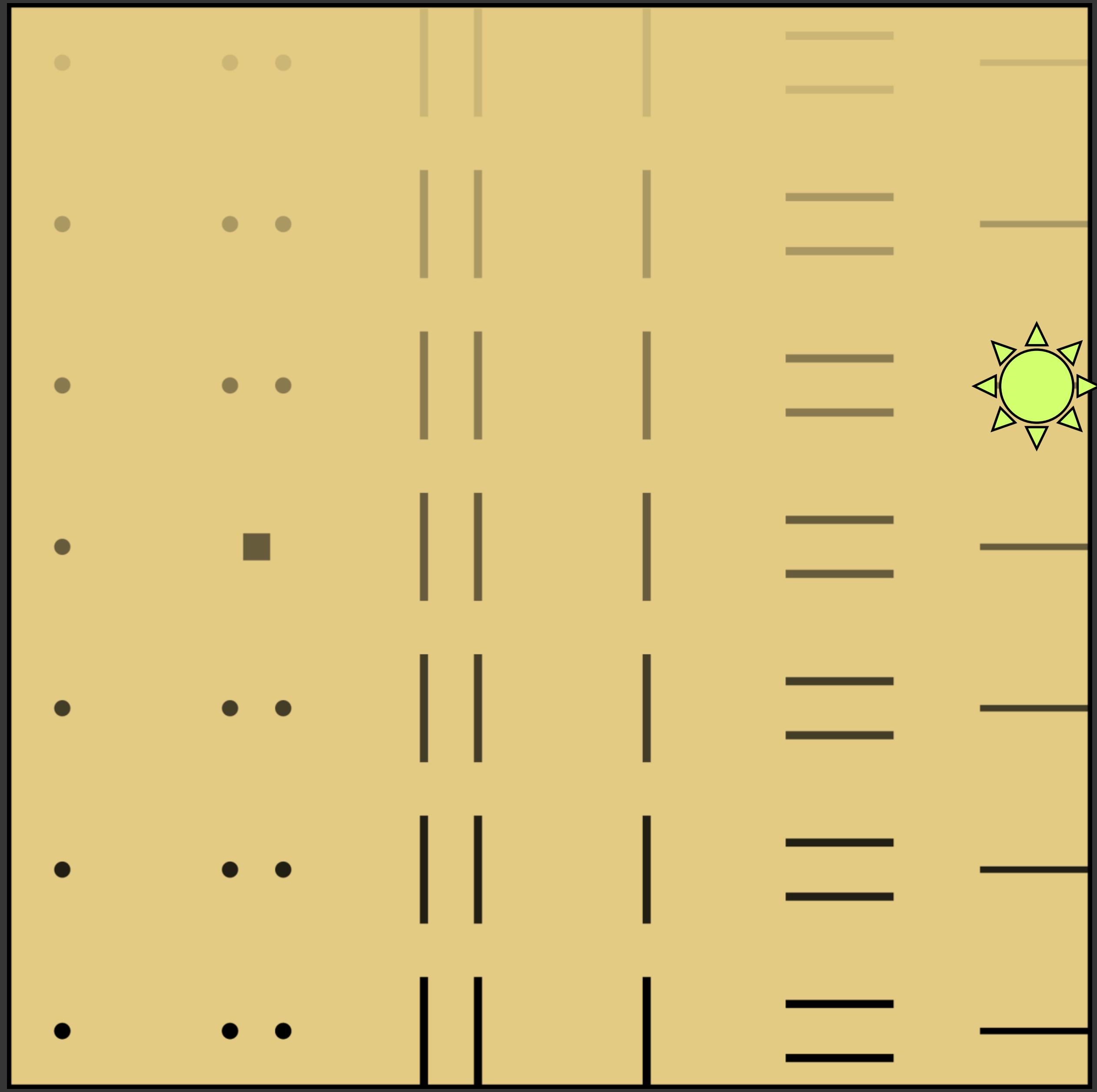


fabricated by
Erik Anderson
CXRO, LBNL

**object-side nanostructures**

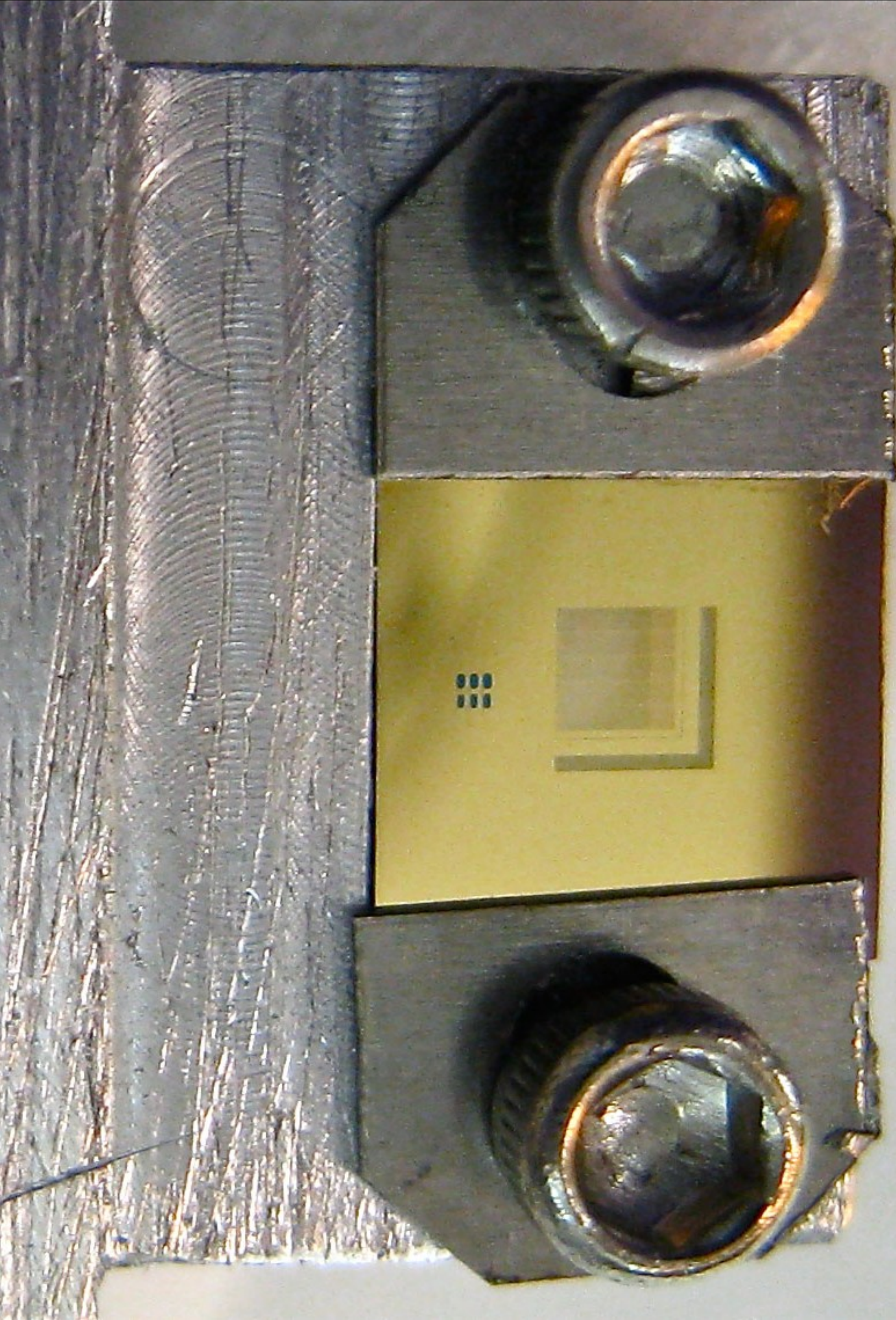
**2-mm wide**

**size gradient**



**pinholes** **slits**

# Image-side nanostructures




fabricated by
Erik Anderson, CXRO, LBNL

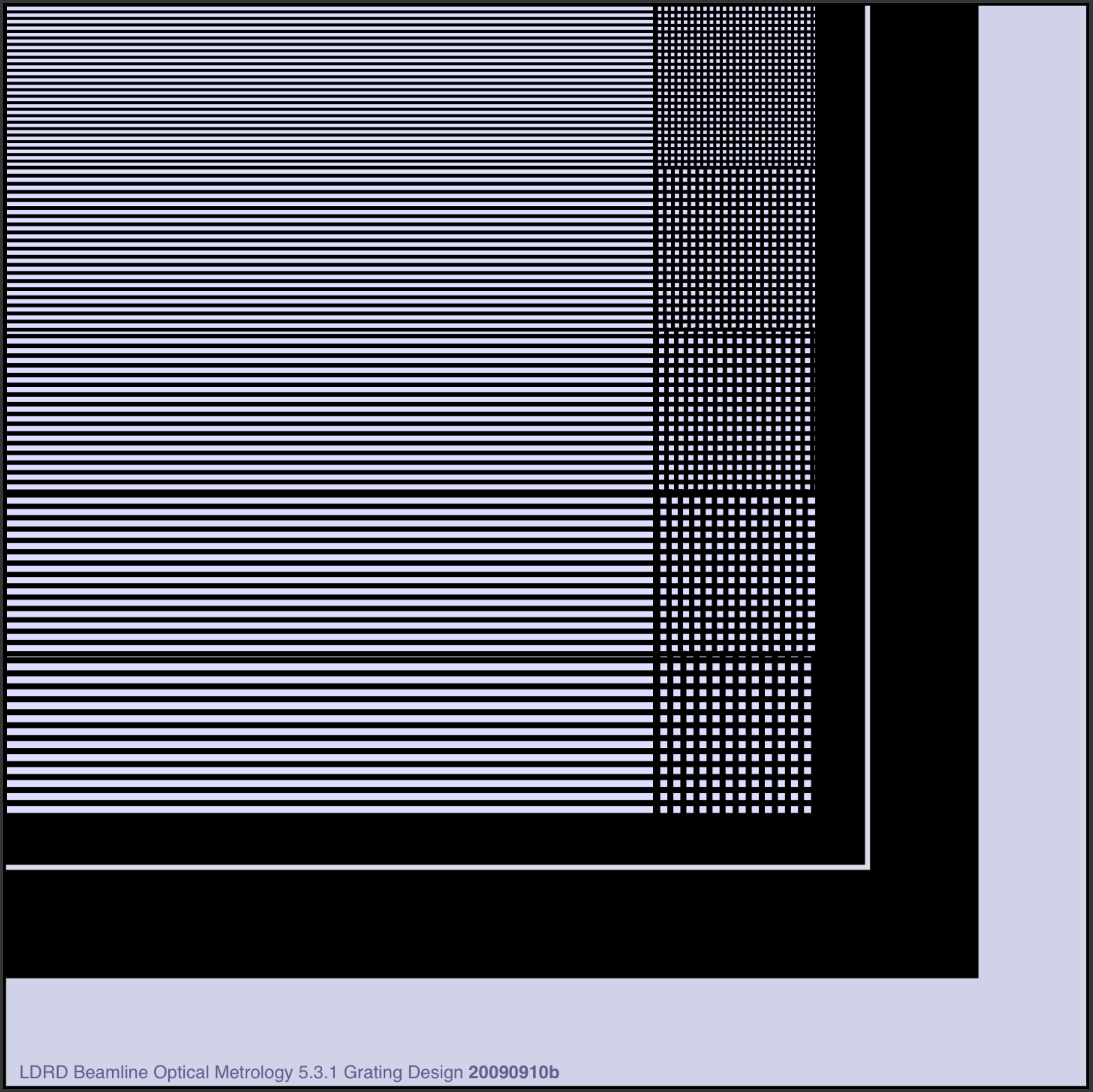
# image-side nanostructures

2-mm wide

gratings (shearing)

10 µm slit

knife-edge




KAGoldberg@lbl.gov

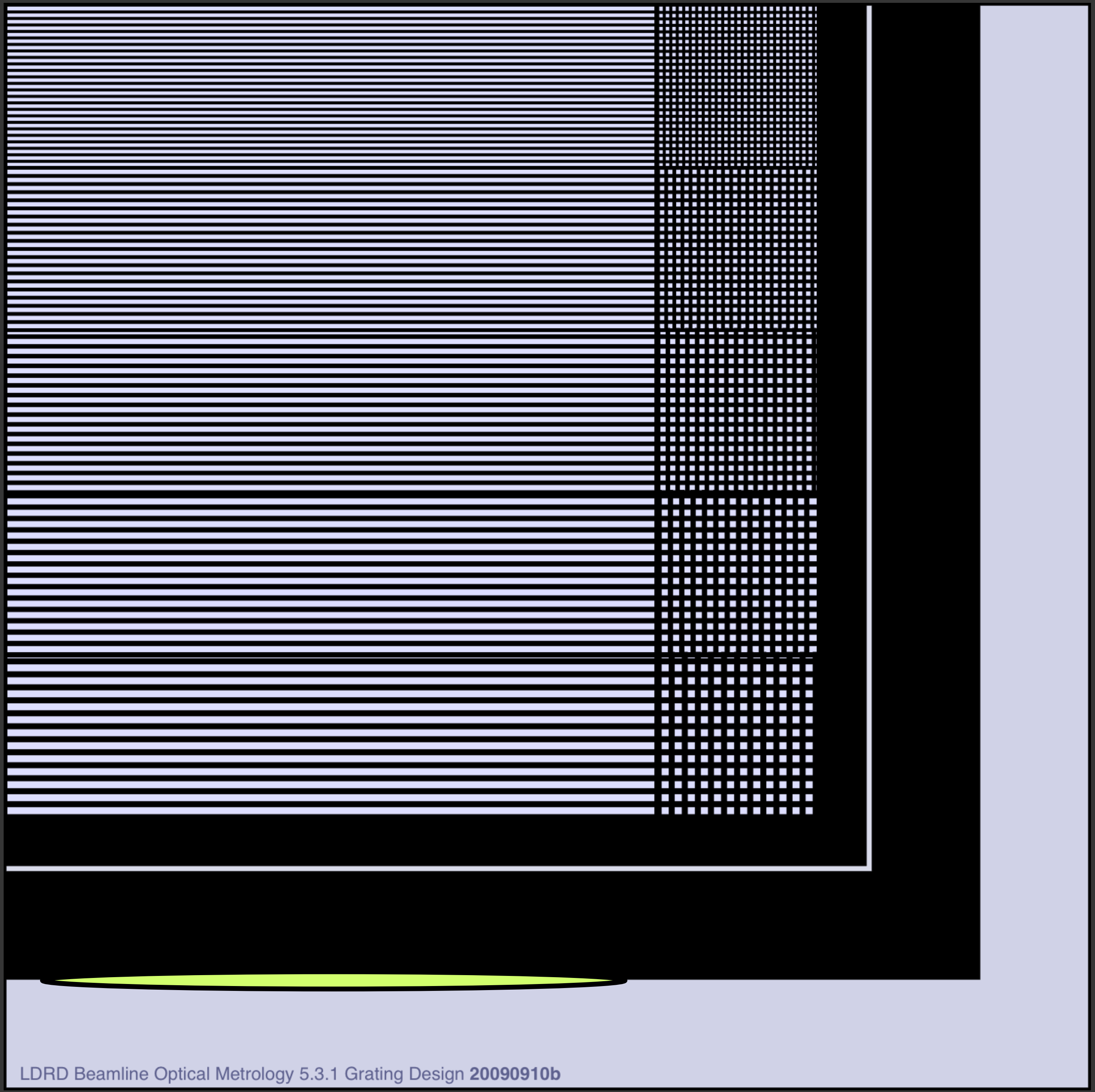
# image-side nanostructures

## 2-mm wide

gratings (shearing)

10 µm slit

**knife-edge**



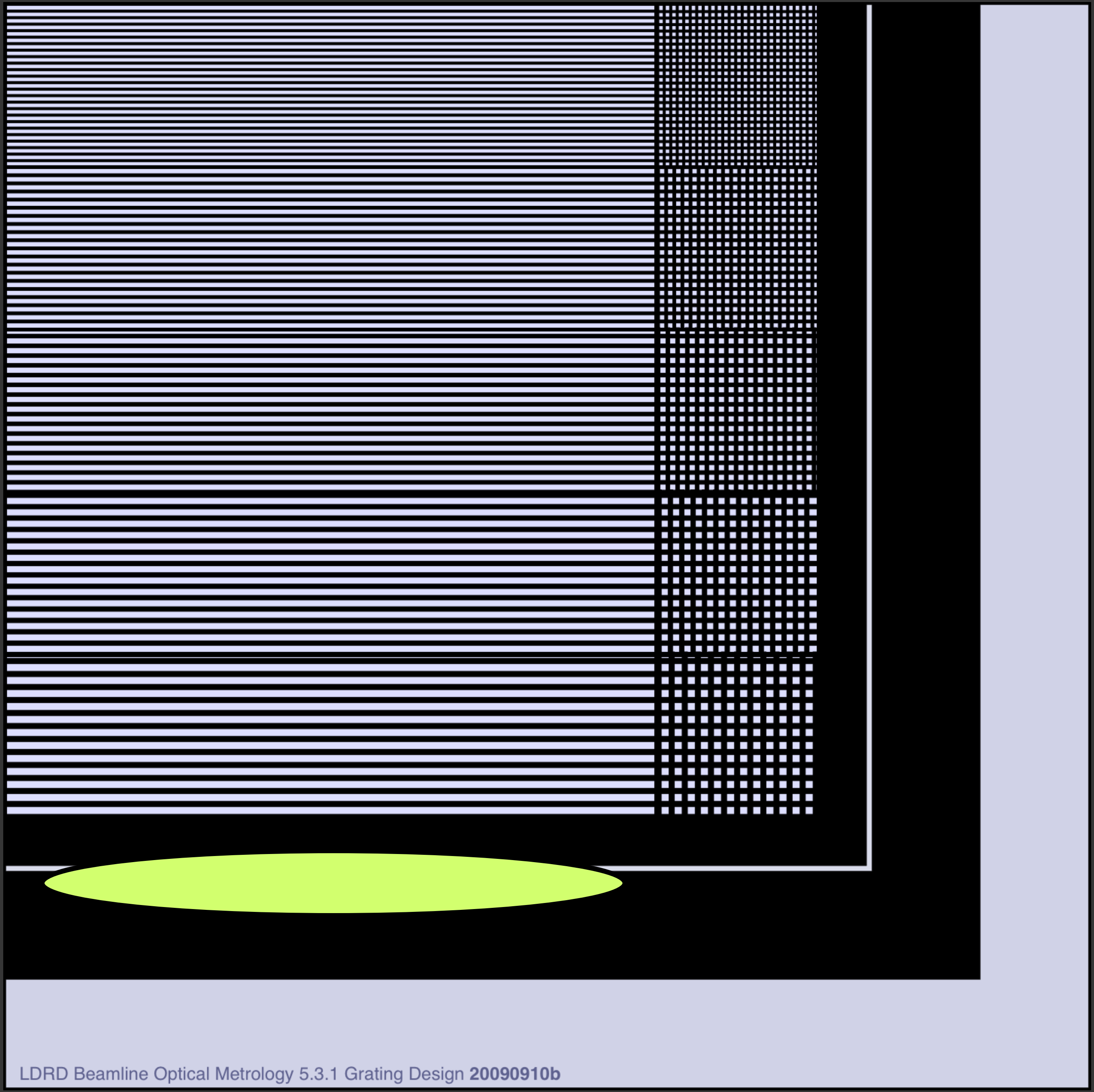
# image-side nanostructures

## 2-mm wide

## gratings (shearing)

**10 µm slit**

## knife-edge




KAGoldberg@lbl.gov

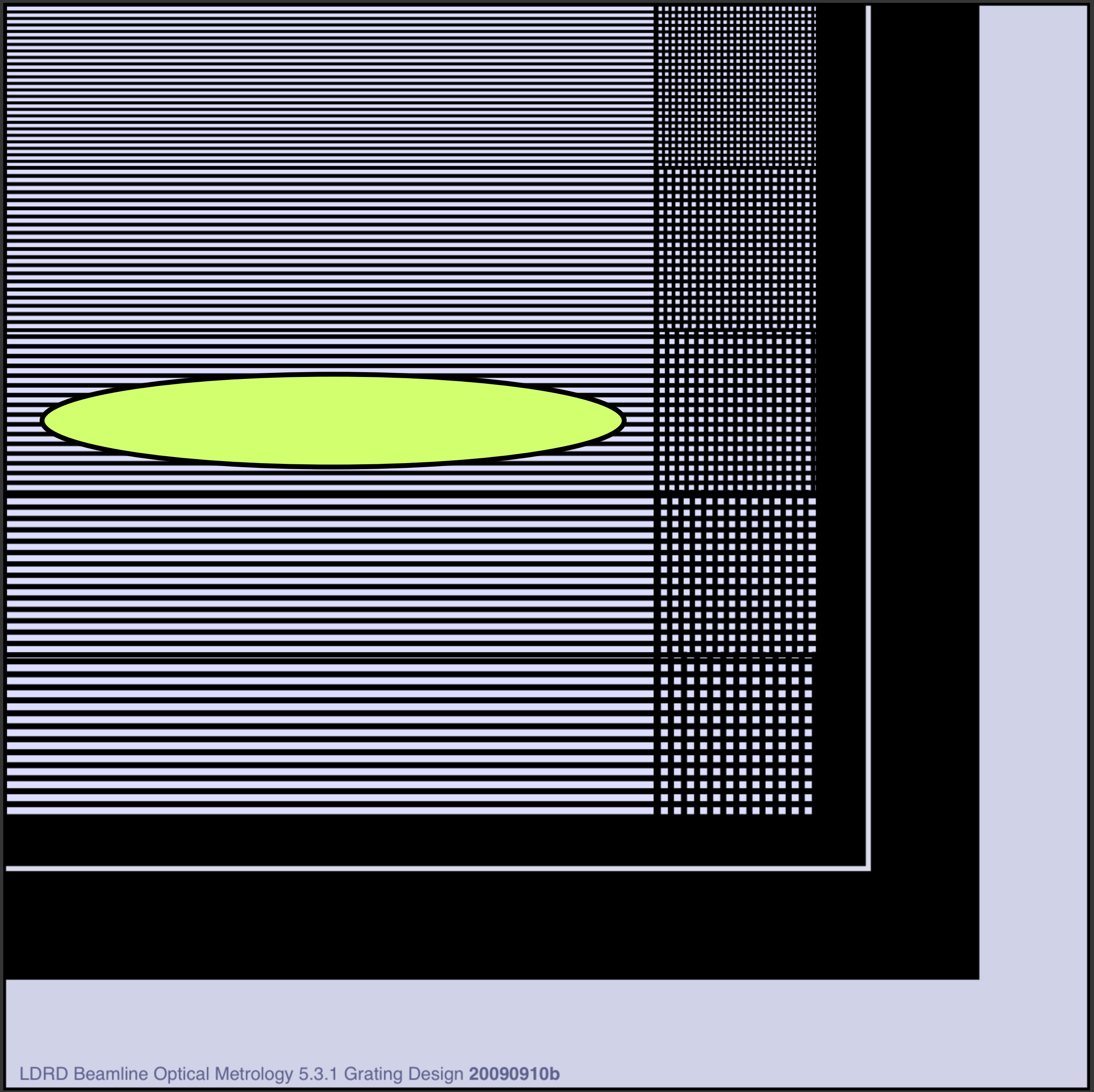
# image-side nanostructures

## 2-mm wide

gratings (shearing)

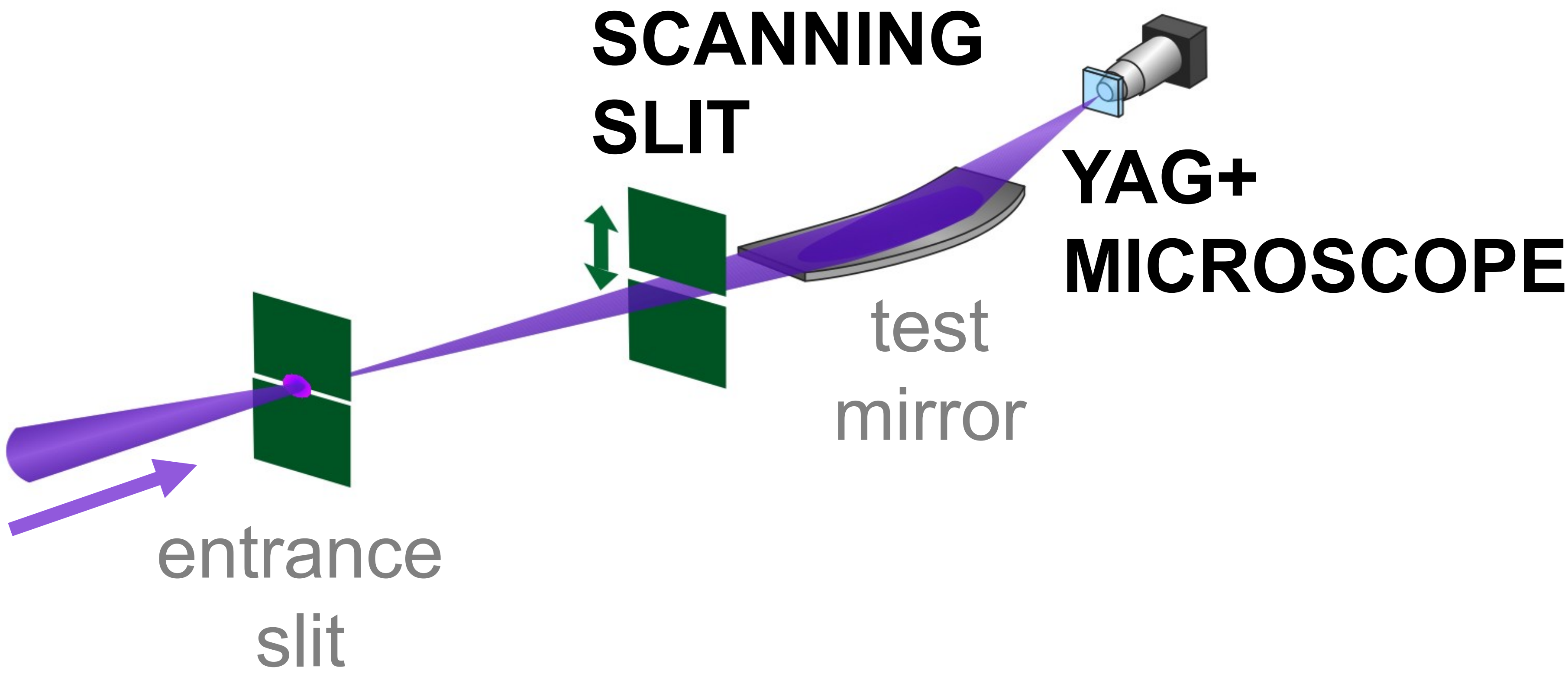
10 µm slit

knife-edge

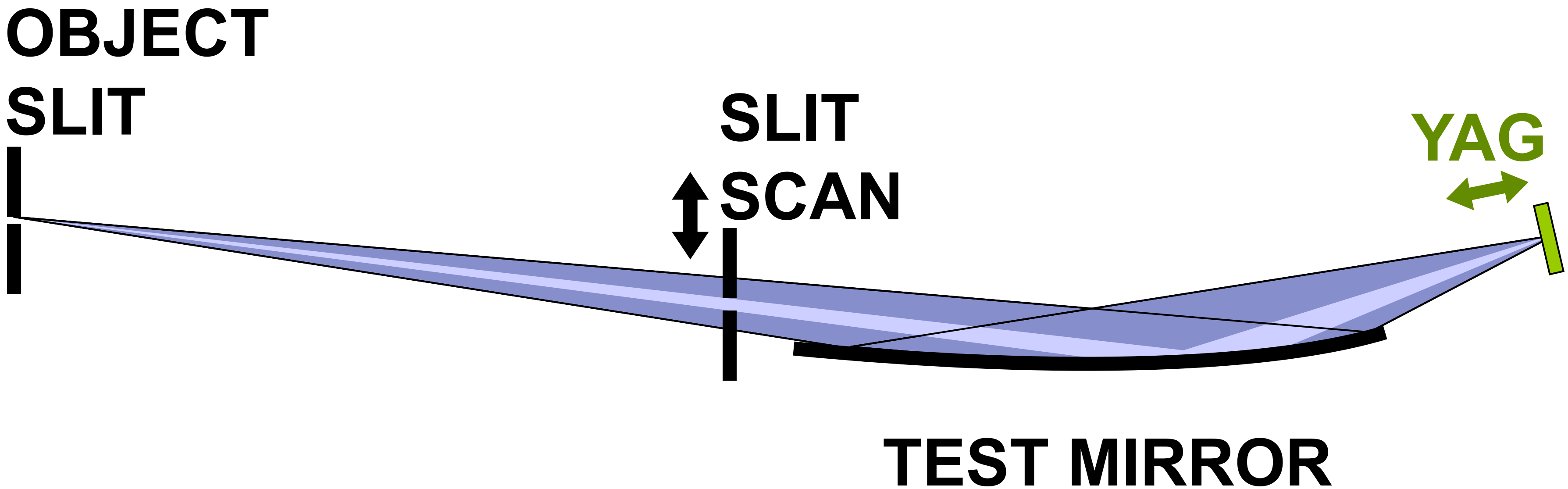


# At-wavelength testing strategies

(Upstream)
Scanning Slit
*on YAG*

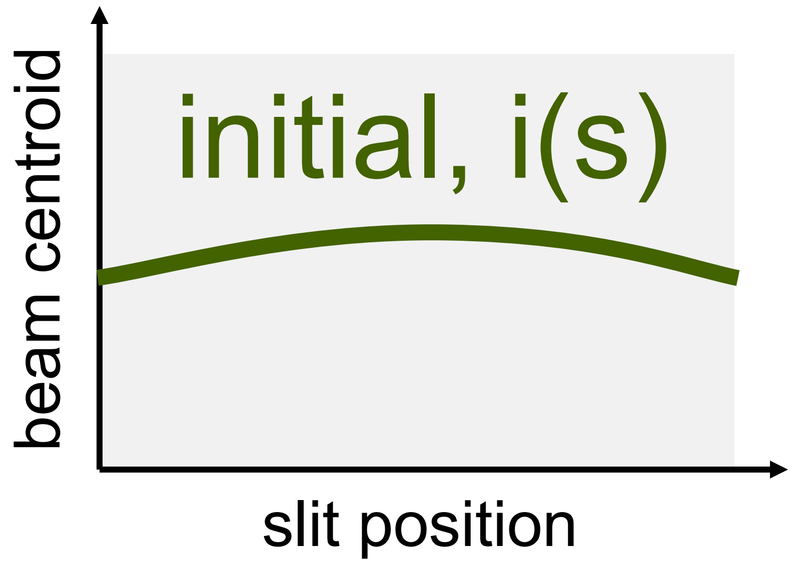


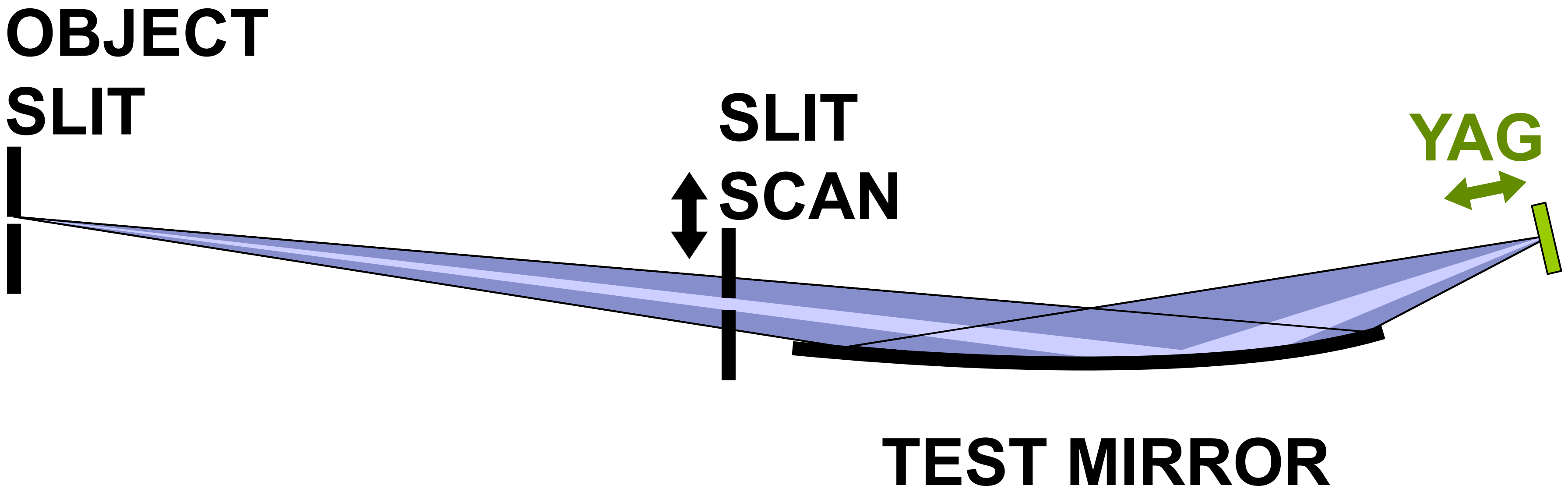
# Linear analysis using characteristic functions

# Linear analysis using characteristic functions

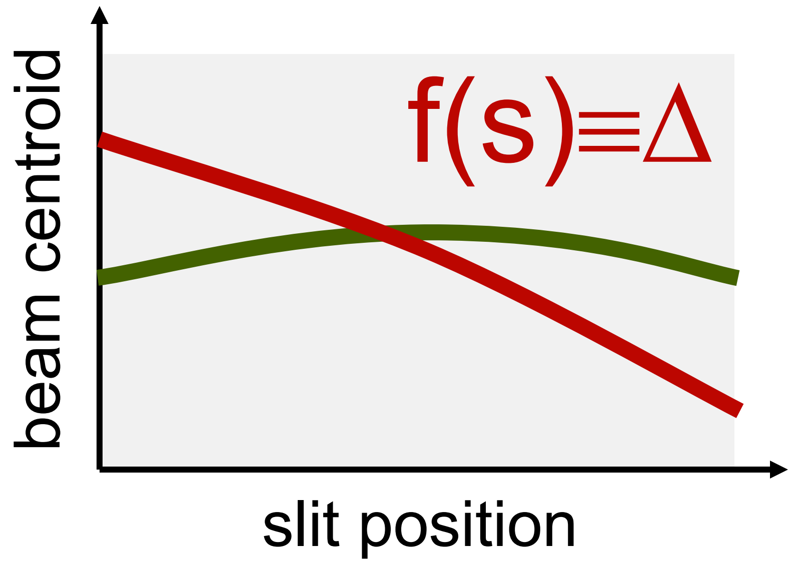
Start with
2 degrees of freedom:
{**Mirror θ**, **YAG Z**}

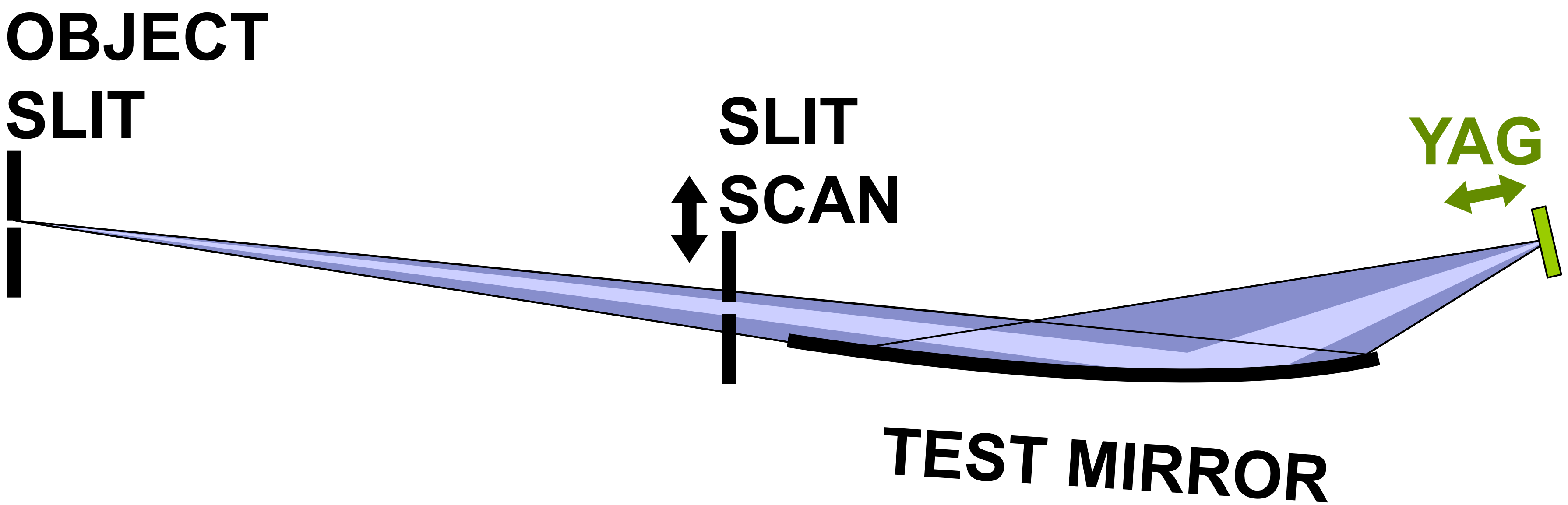


# Linear analysis using characteristic functions

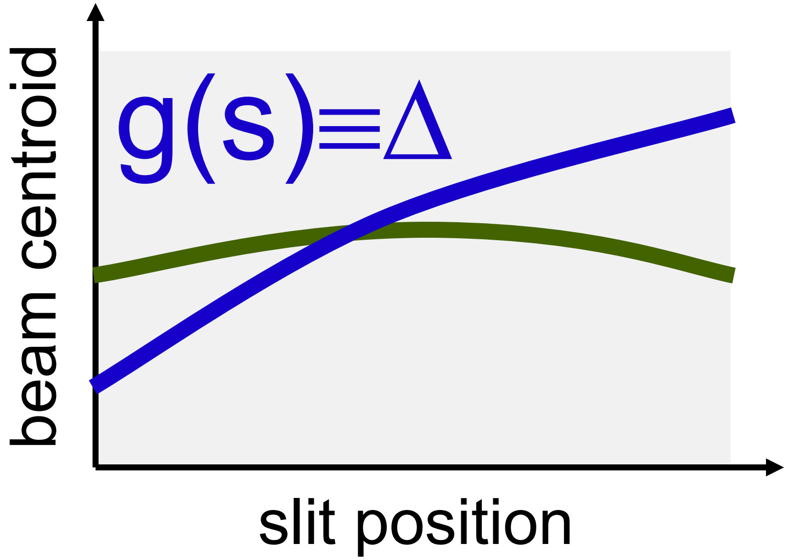
Adjust **Mirror θ**:
note the *change*

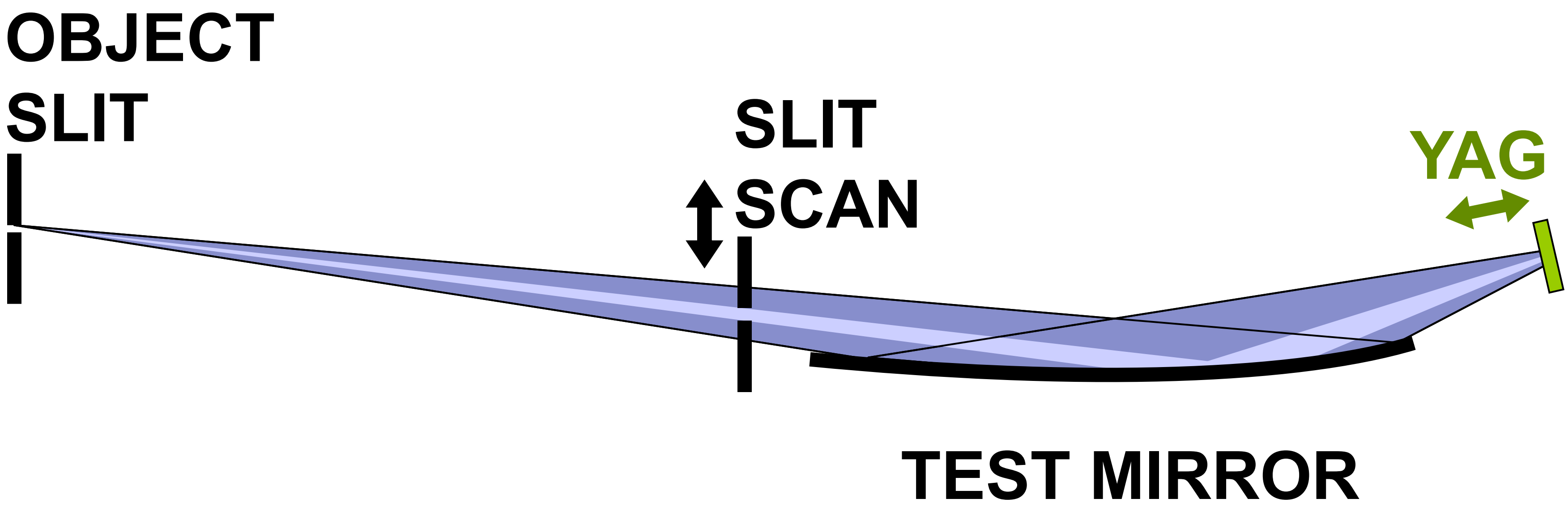


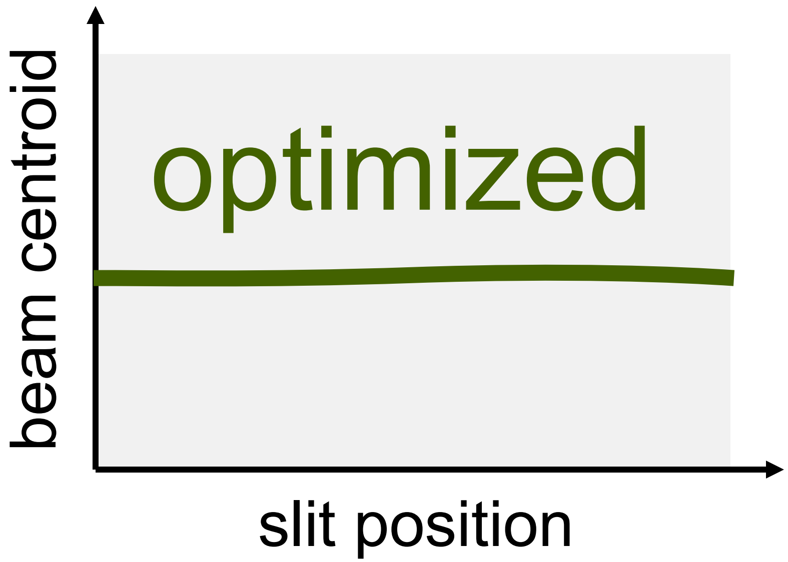
# Linear analysis using characteristic functions

Adjust **YAG Z**:
note the *change*



# Linear analysis using characteristic functions



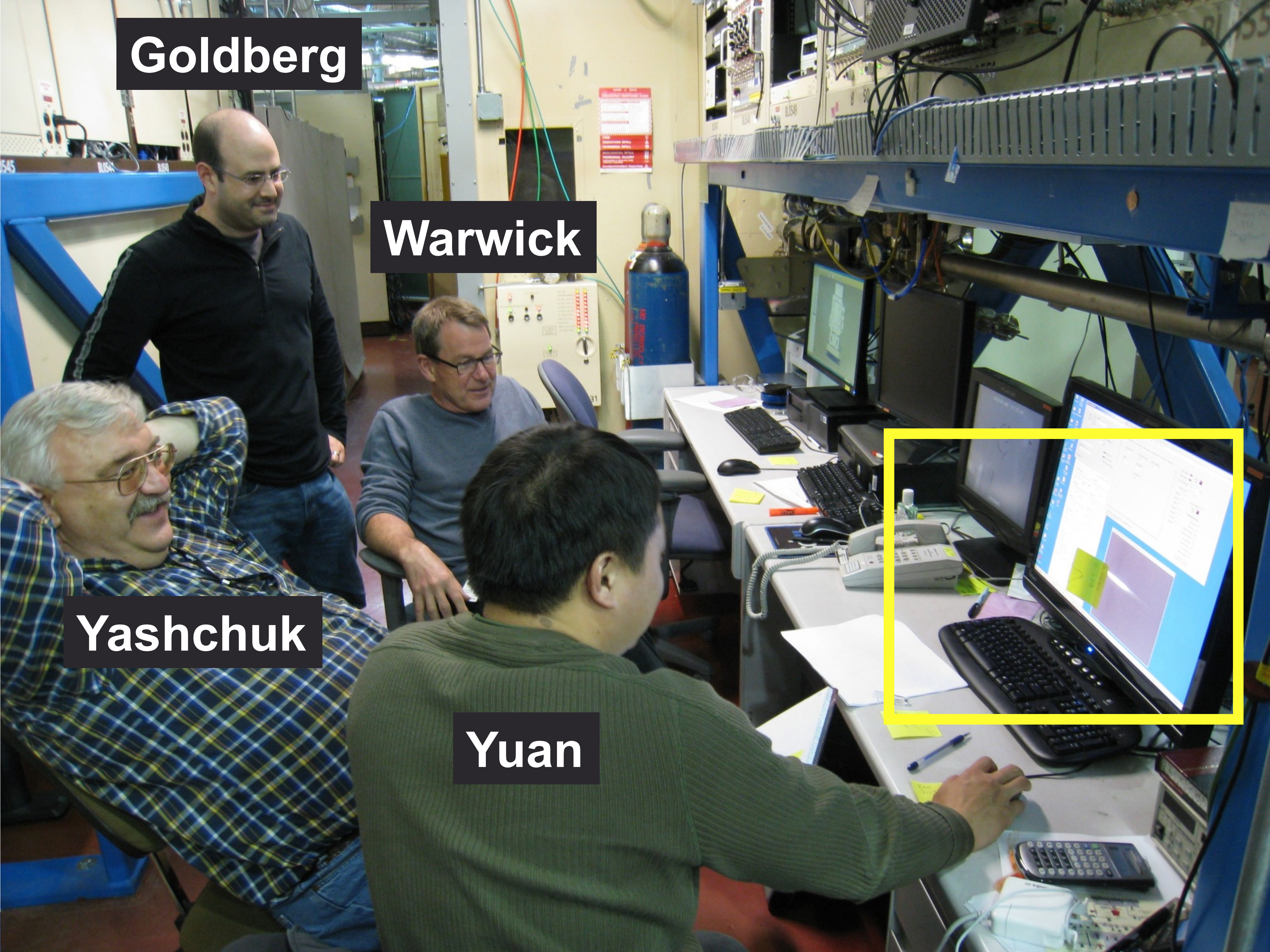

**Minimize** with {**a**, **b**}

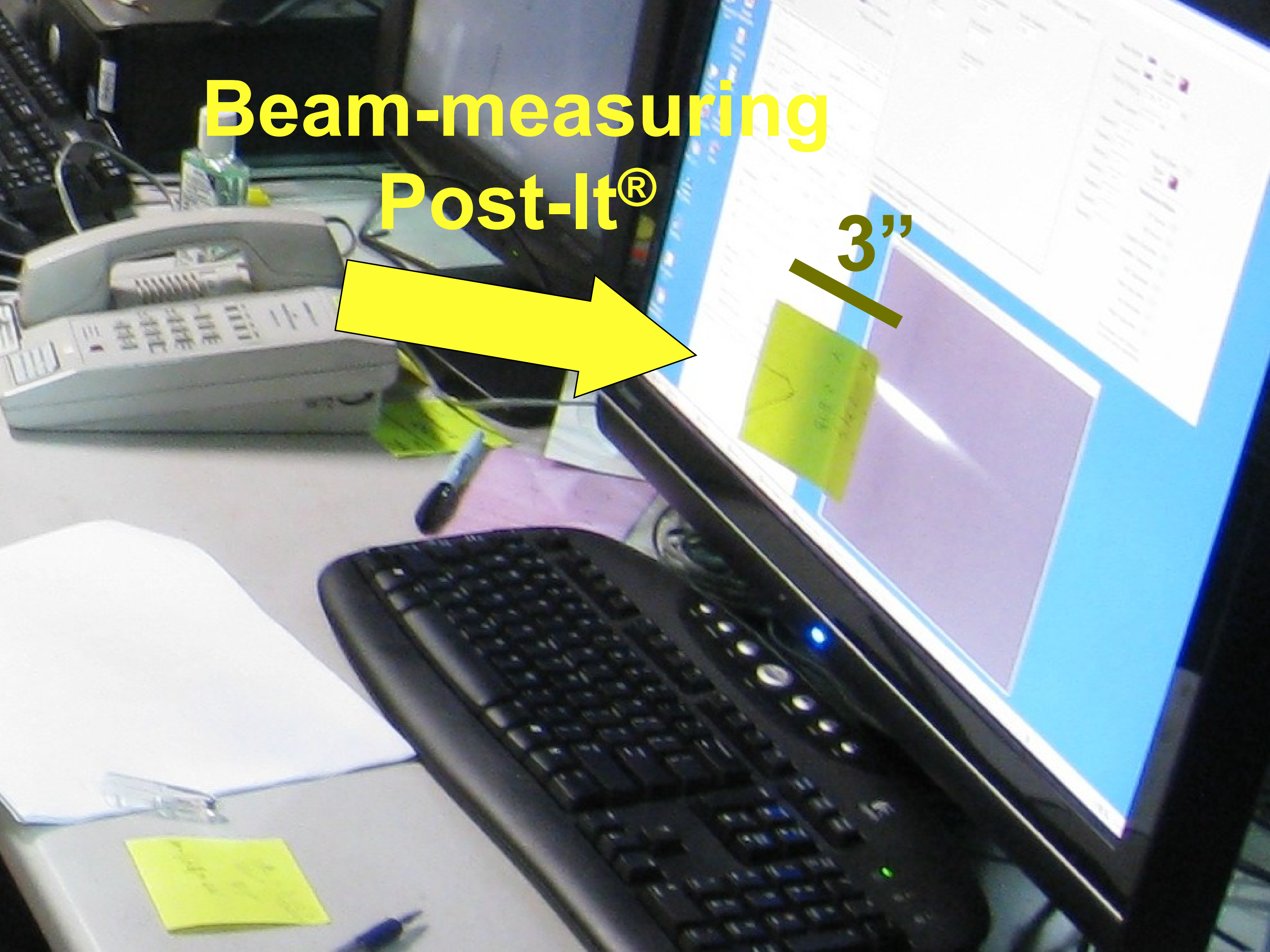
$$\text{Error}^2 = \sum\left\{i(s) - [\mathbf{a}\, f(s) + \mathbf{b}\, g(s)]\right\}^2$$

**a = Mirror Δθ**

**b = YAG ΔZ**

Yuan, *SPIE* **7801**


Goldberg
Warwick
Yashchuk
Yuan

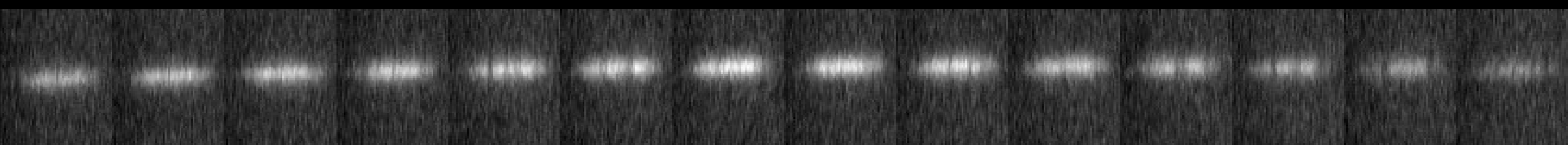

Beam-measuring
Post-It®
3”

# Upstream Slit Scan: *Viewed on YAG (visible)*

## Measure centroid motion to calculate slope

0.8 μm effective pixel size

Each pixel is ~6.7 μrad



***slit motion*** →

image details compressed horizontally

100224 194–207

# Upstream Slit Scan: *Viewed on YAG*

## Measure centroid motion to calculate slope

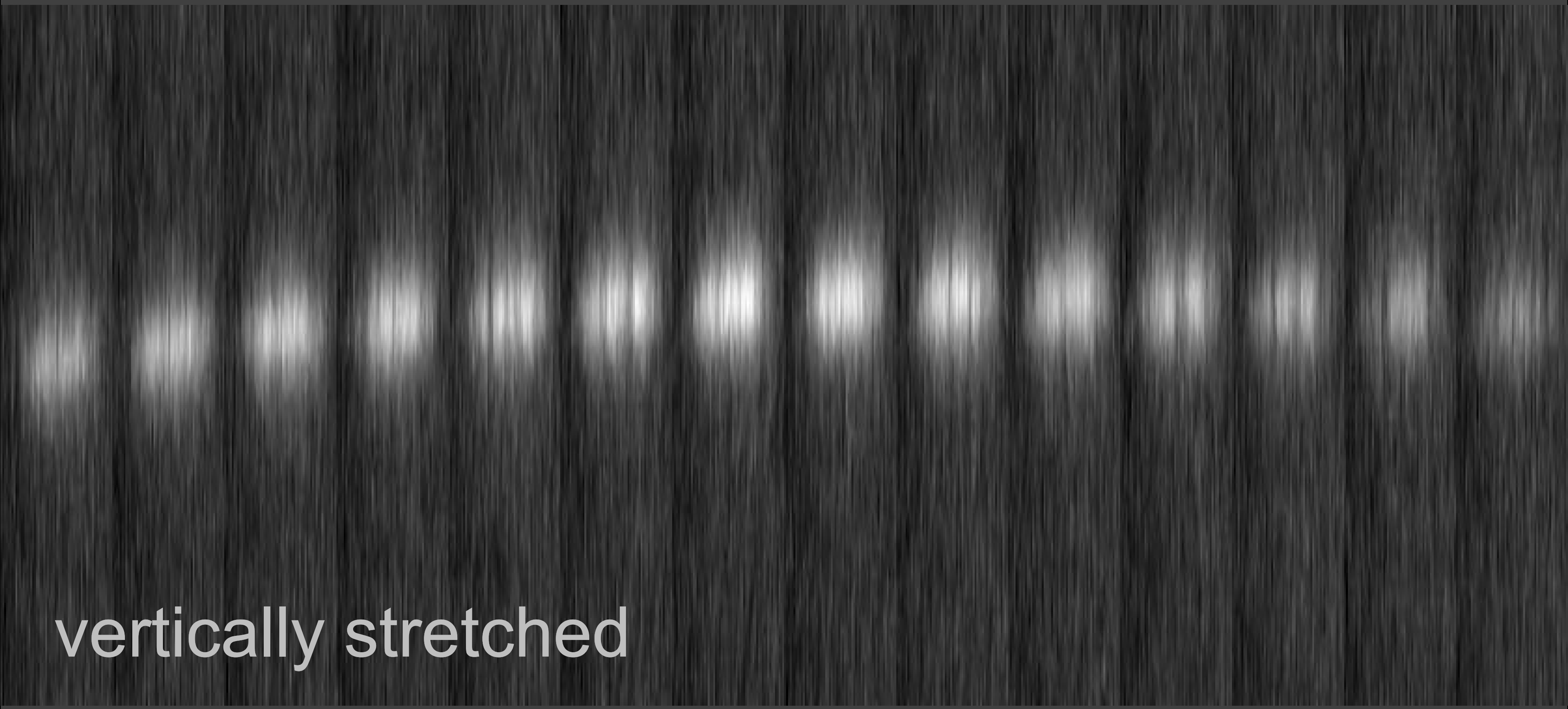
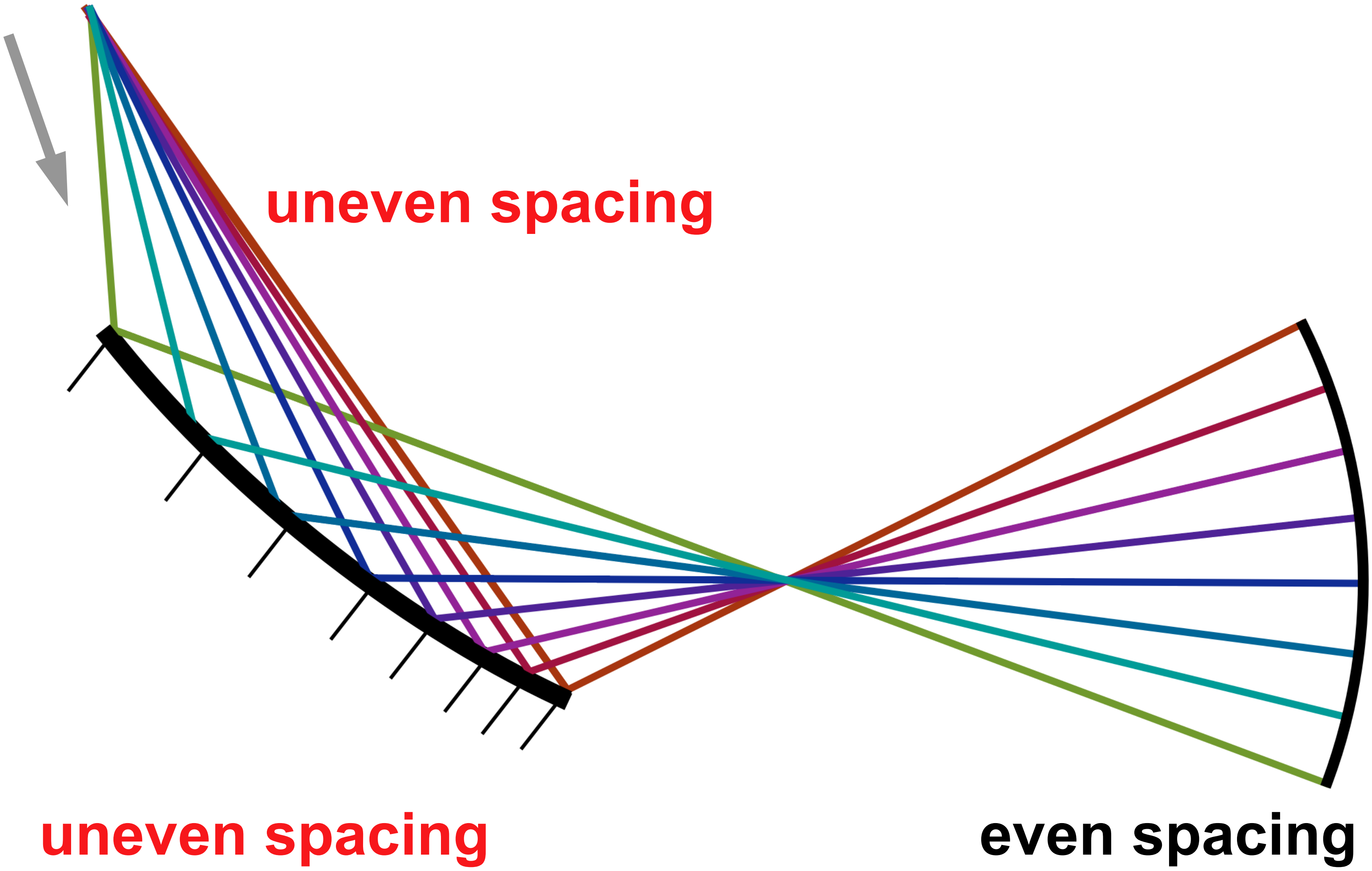



image details compressed horizontally

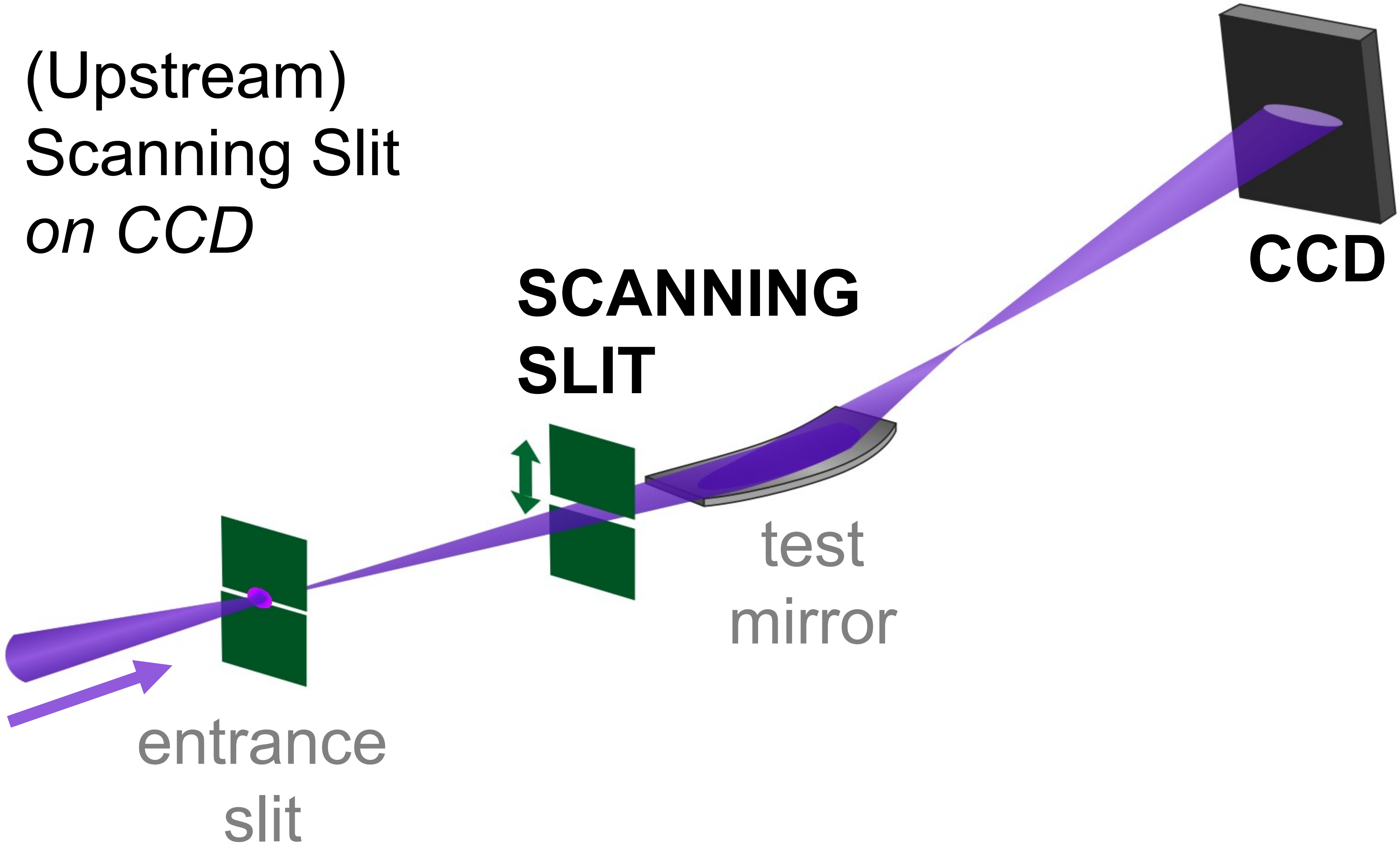
100224 194–207

# Coordinate transformation requires mapping

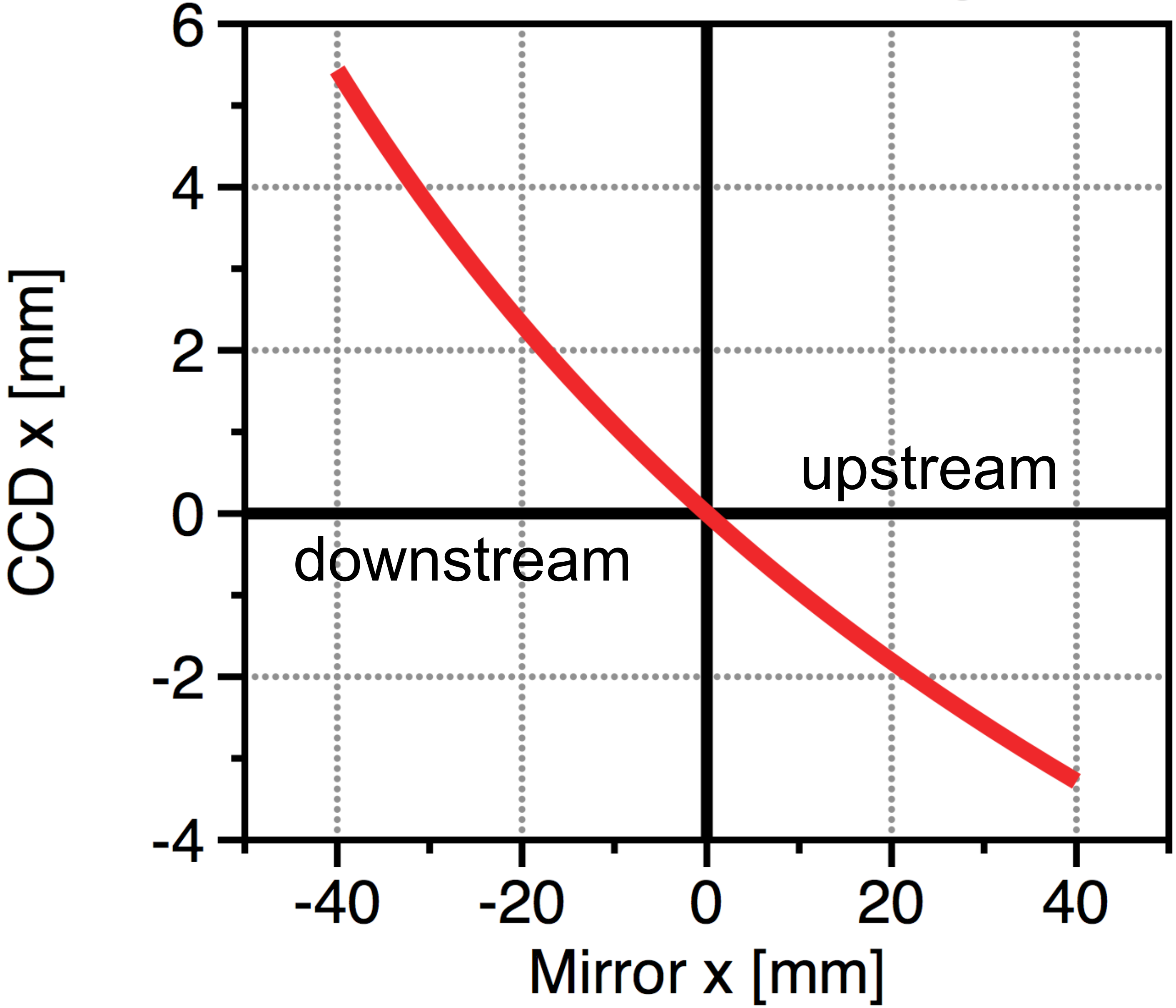


# At-wavelength testing strategies

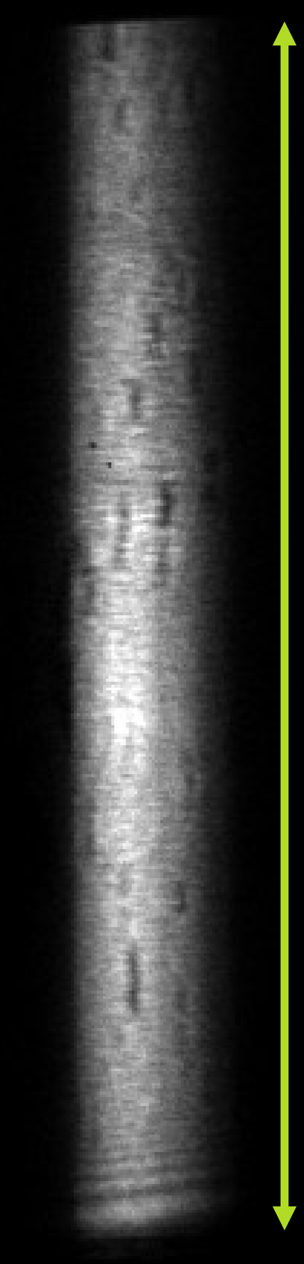
(Upstream)
Scanning Slit
*on CCD*



# Coordinate Mapping



# The projected pupil

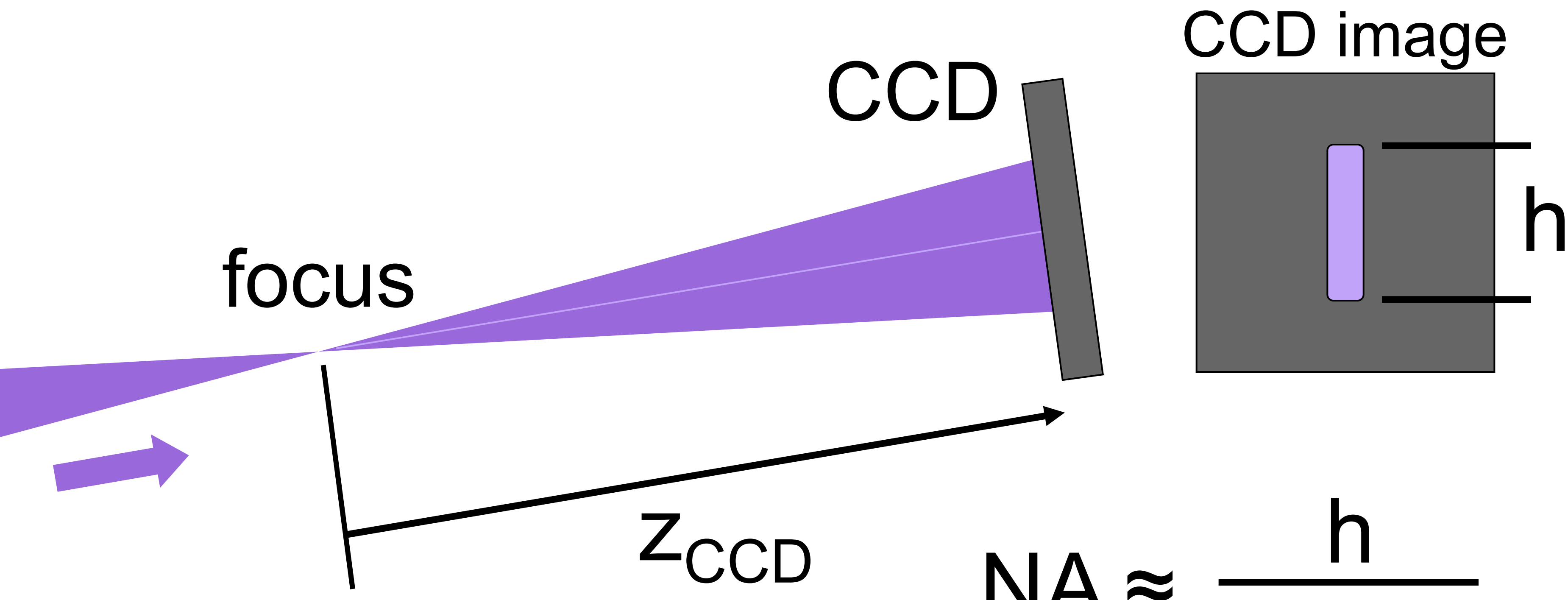


h = 415 pixels,
24 µm/pixel
= 9.96 mm

$Z_{CCD}$ = 1.522 m

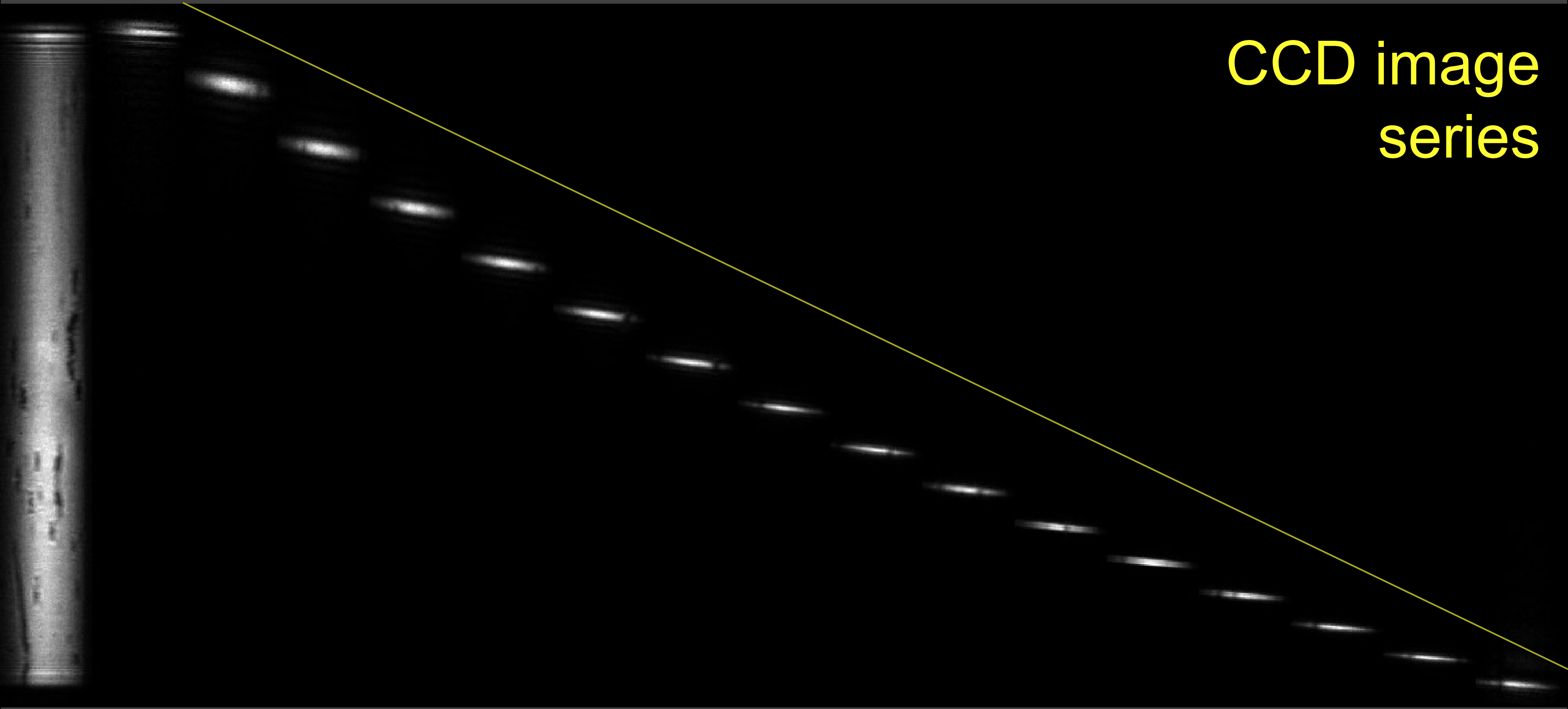
**NA = 3.27 mrad**

# Calculate NA from the CCD image




$$NA \approx \frac{h}{2\, z_{CCD}}$$

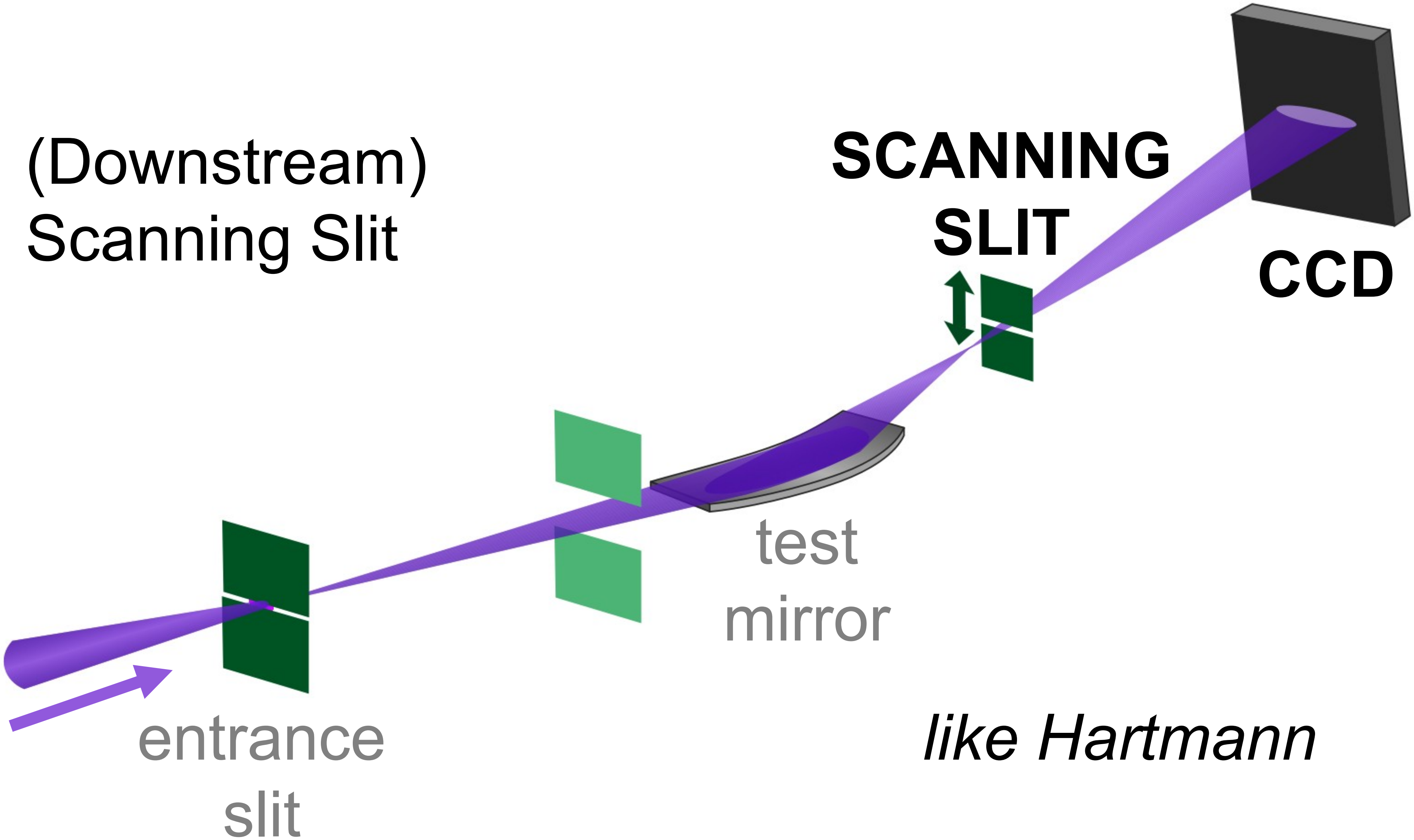
# Upstream Scanning Slit




***slit motion*** →

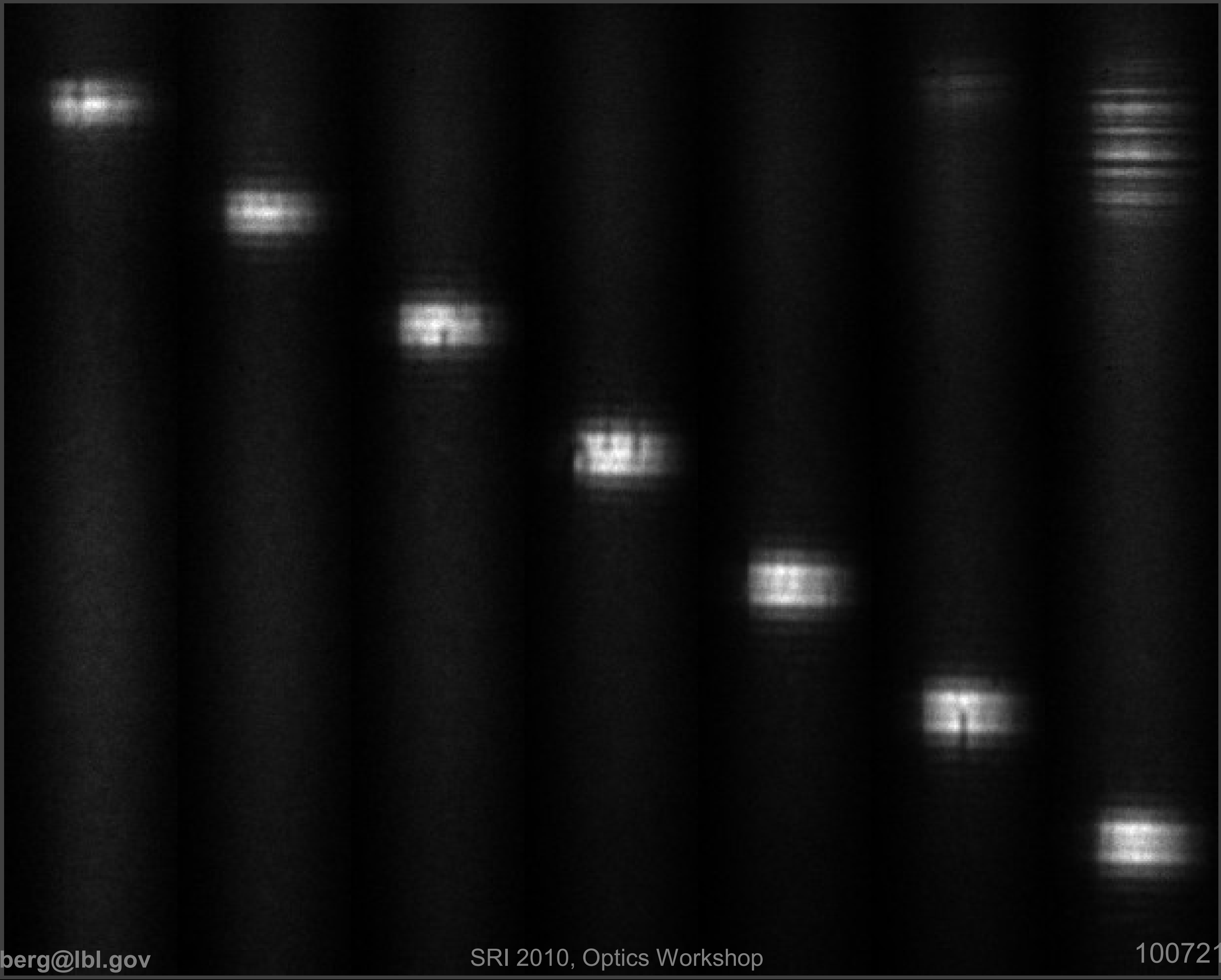
# At-wavelength testing strategies

(Downstream)
Scanning Slit

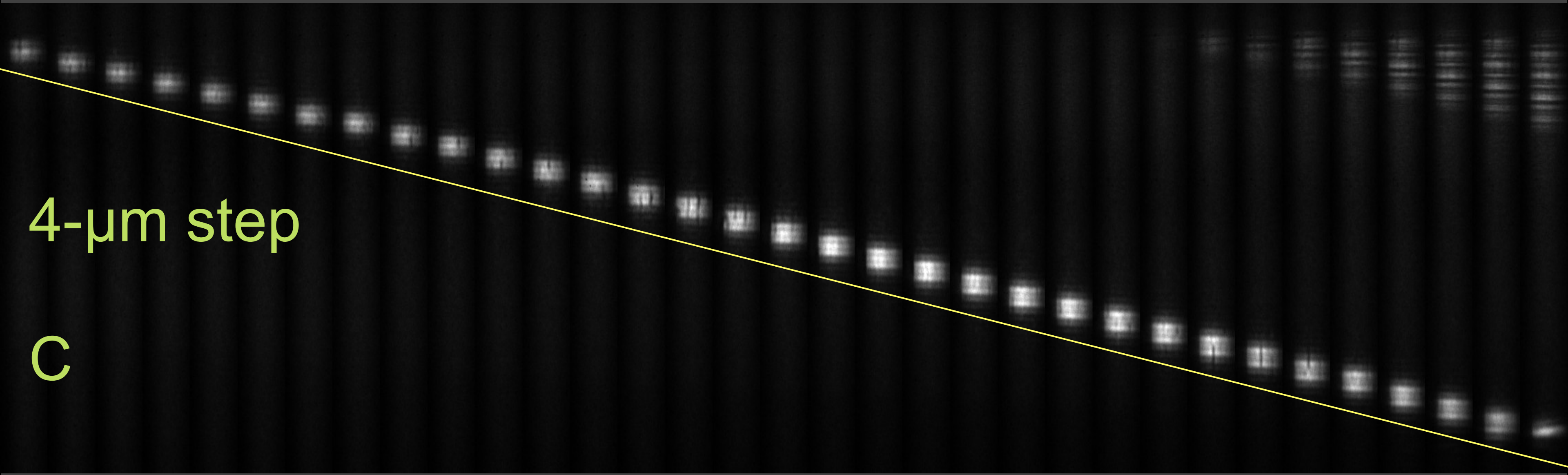



*like Hartmann*

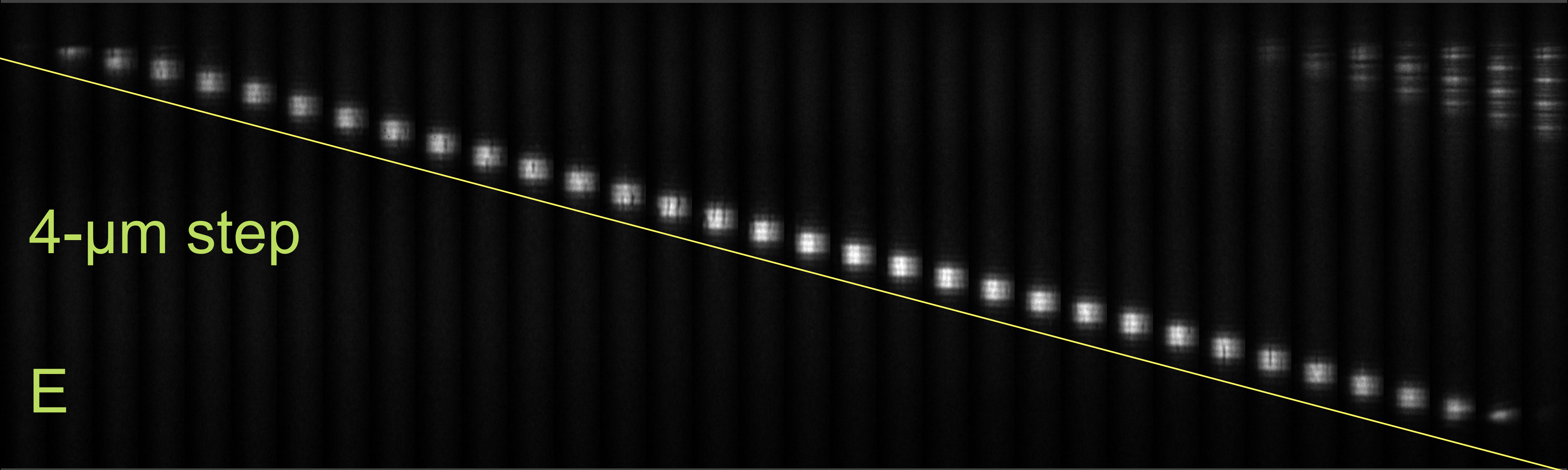
# **Downstream Scanning Slit**, sample



# Downstream Scanning Slit



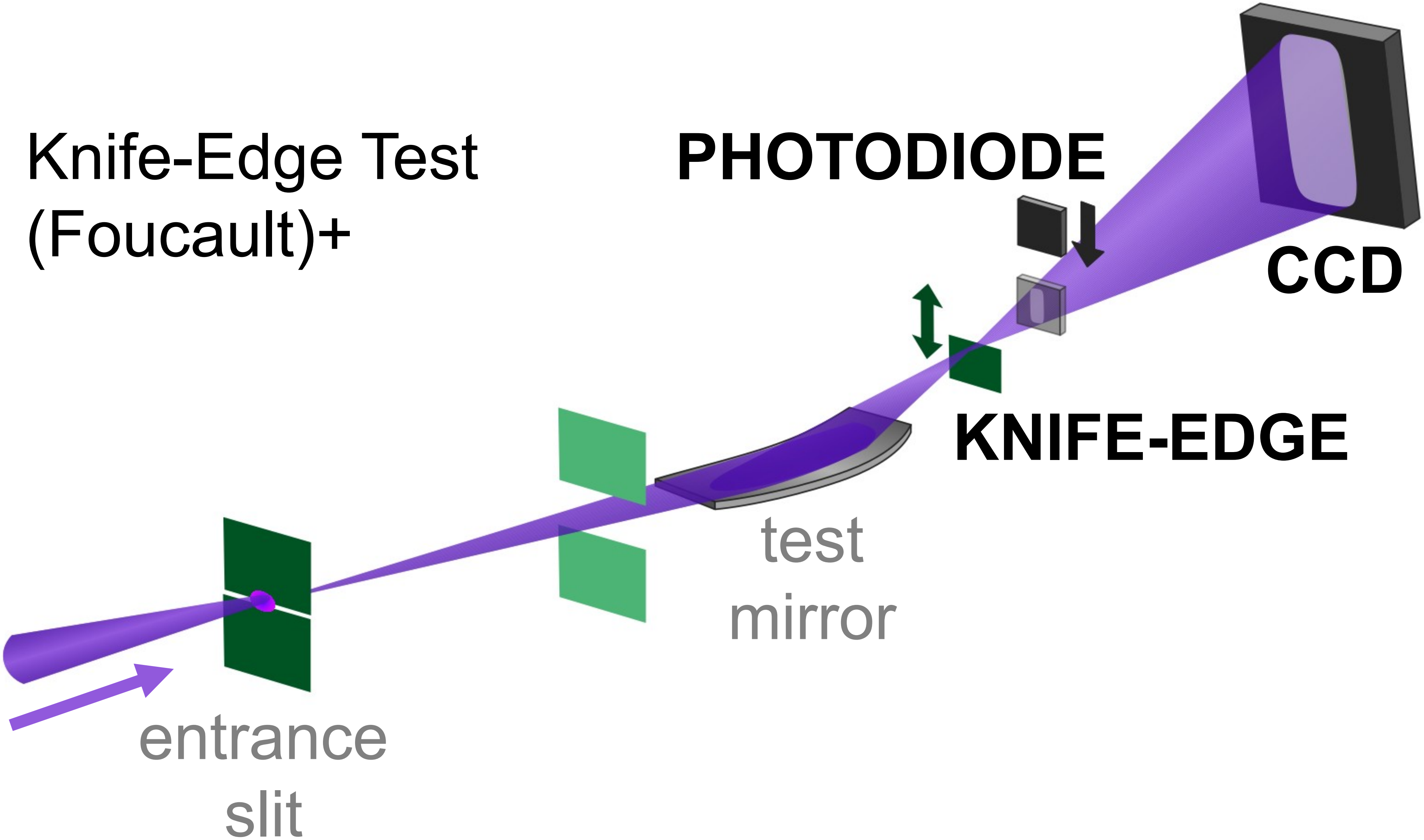

100721_0015



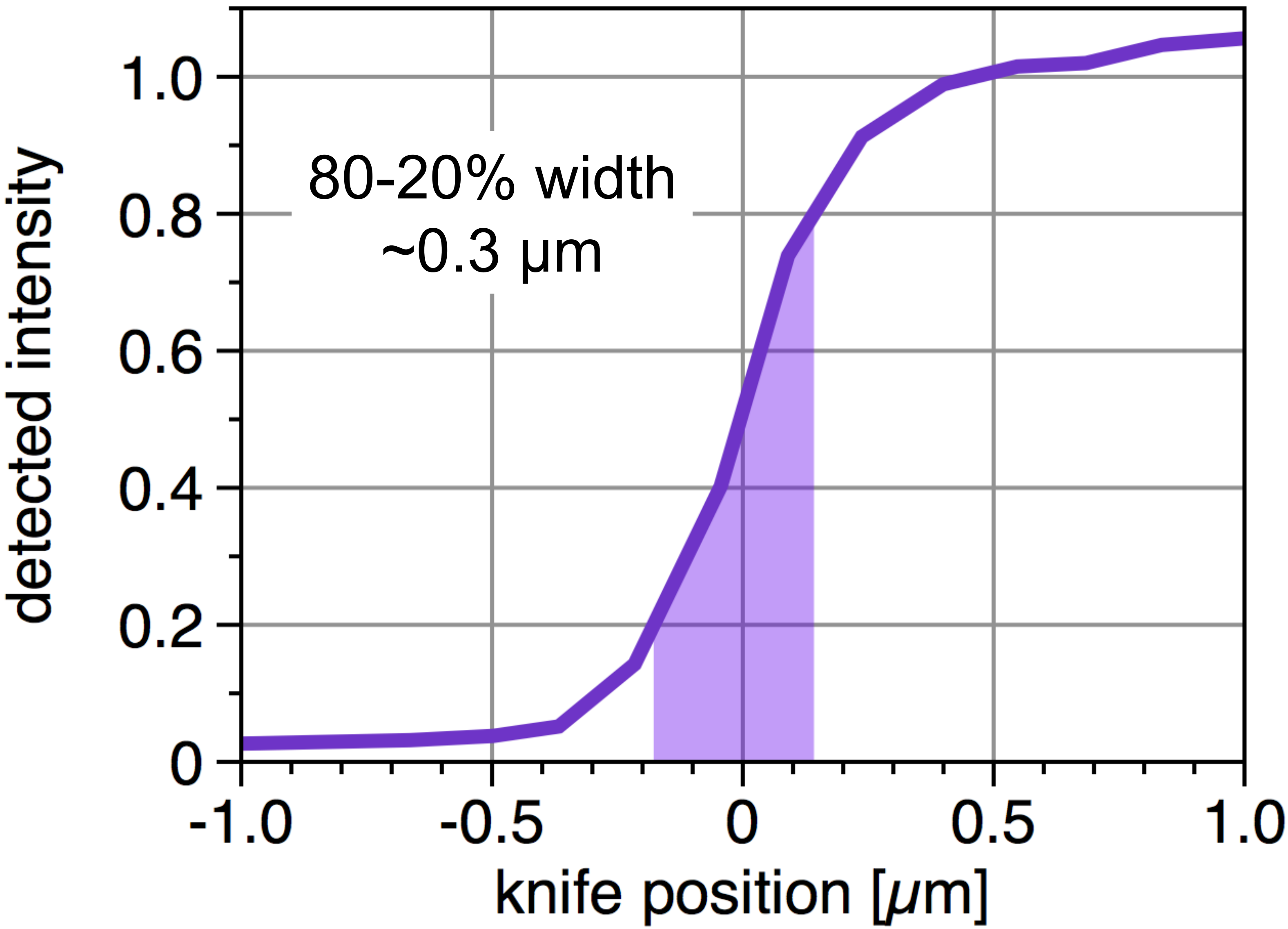

100723_0023

# At-wavelength testing strategies

Knife-Edge Test (Foucault)+



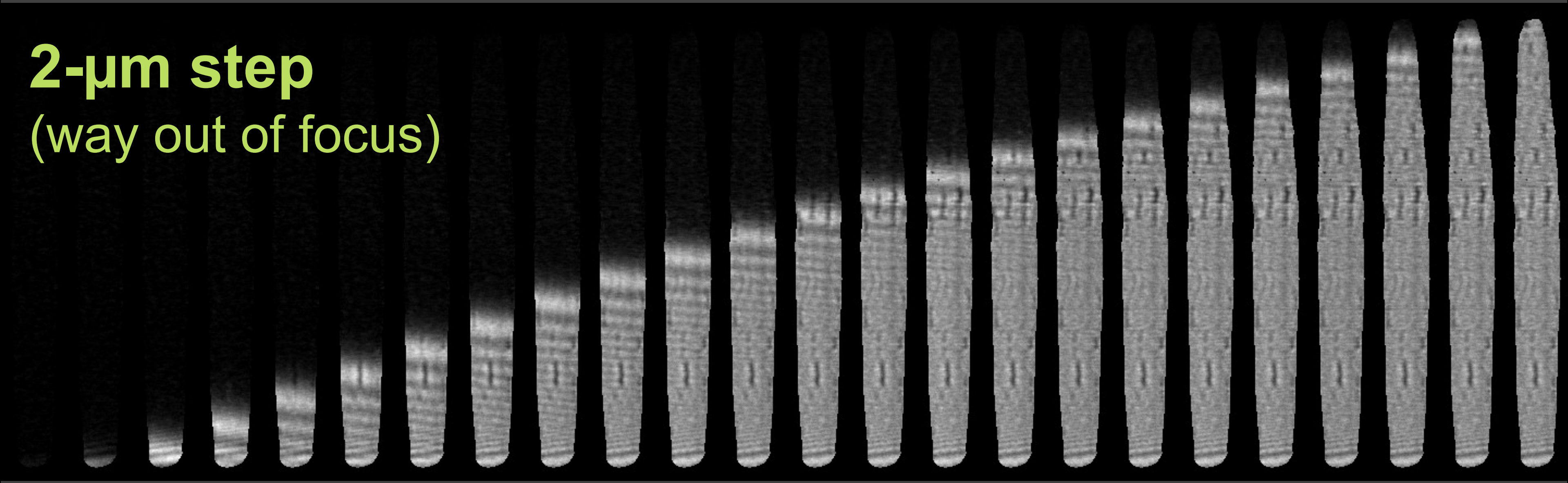
# Simple Knife-Edge Scan



# Knife Edge Scans—on CCD

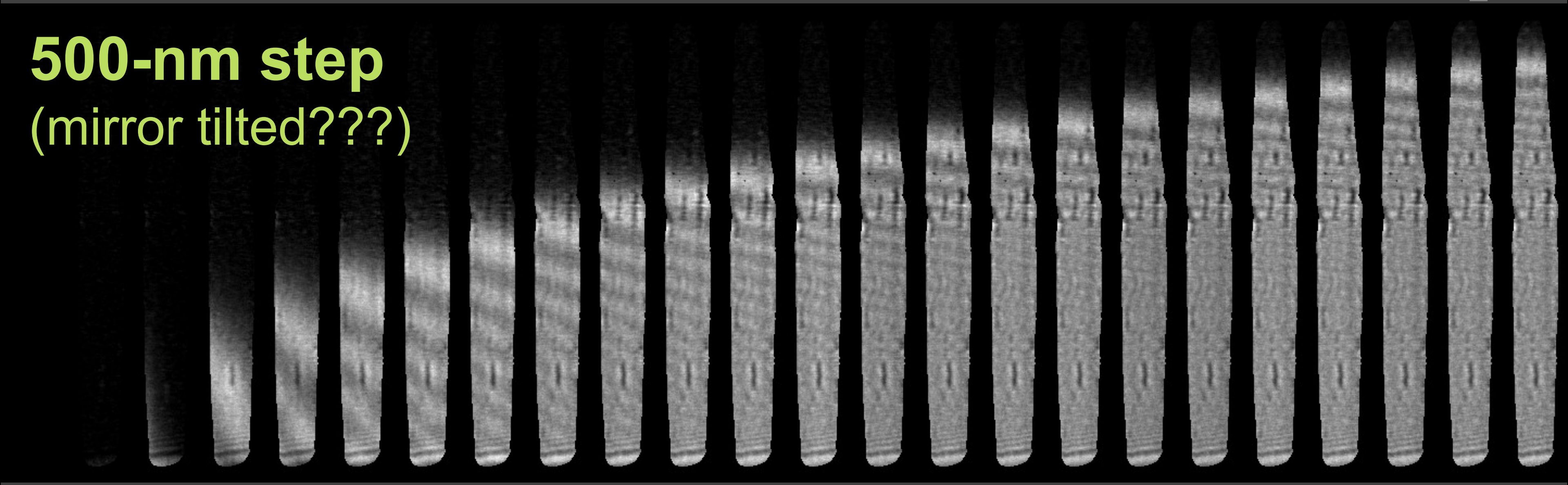
intensity normalized

**2-µm step**
(way out of focus)



100721_0013

**500-nm step**
(mirror tilted???)



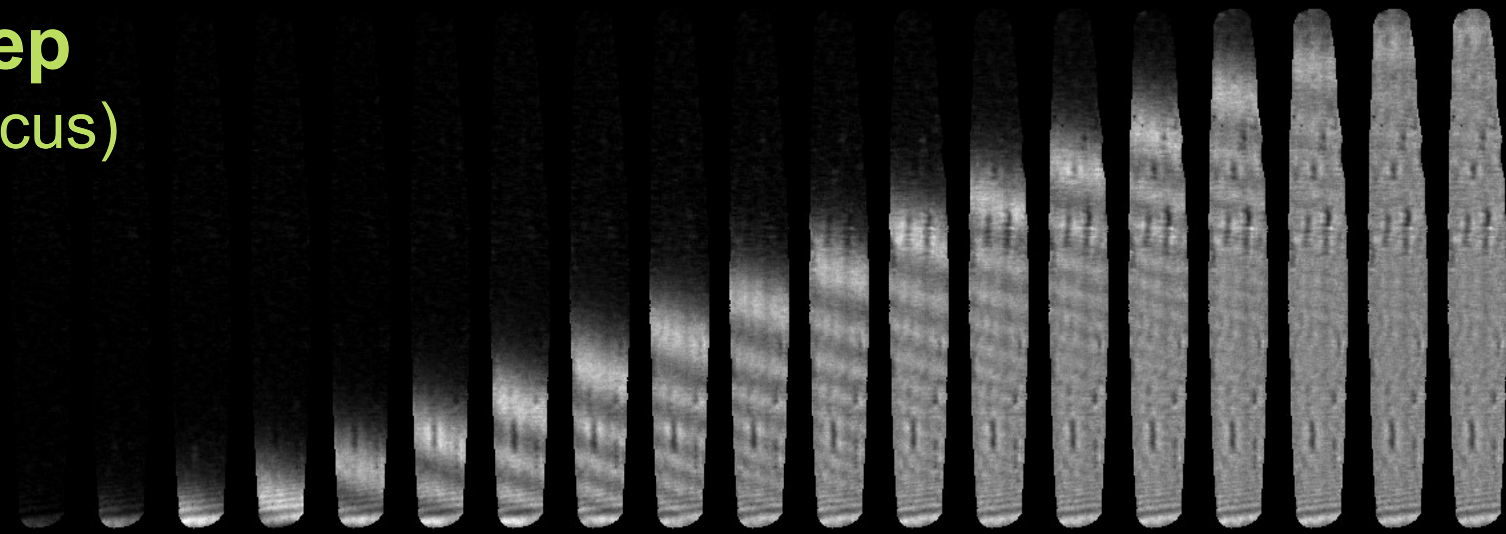
100721_0019

# Knife Edge Scans—on CCD

intensity normalized

**600-nm step**

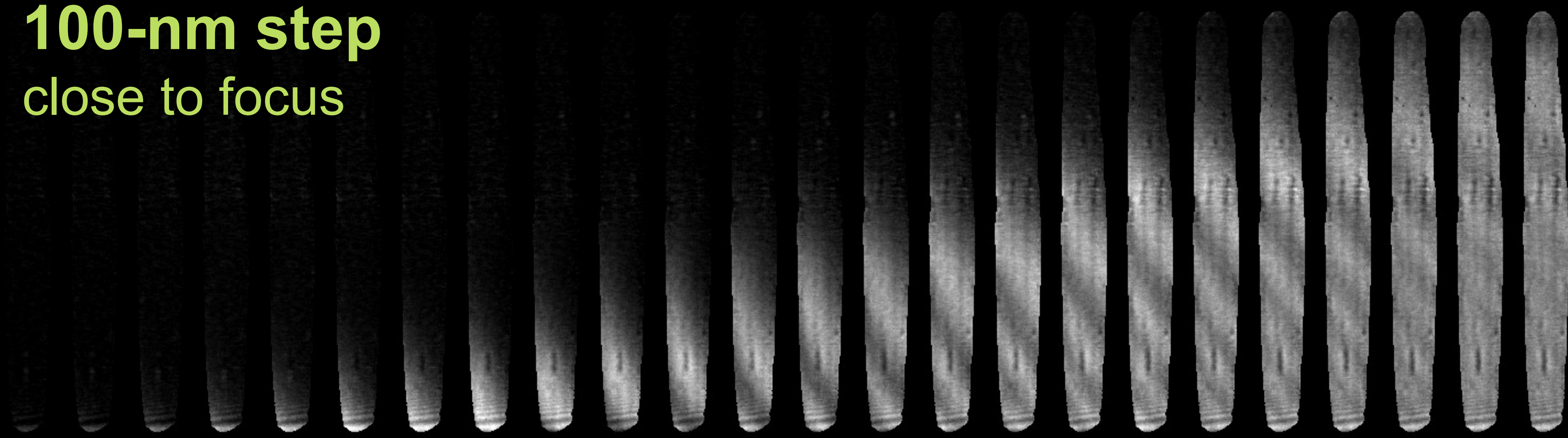
(still out of focus)



100722_0021

**100-nm step**

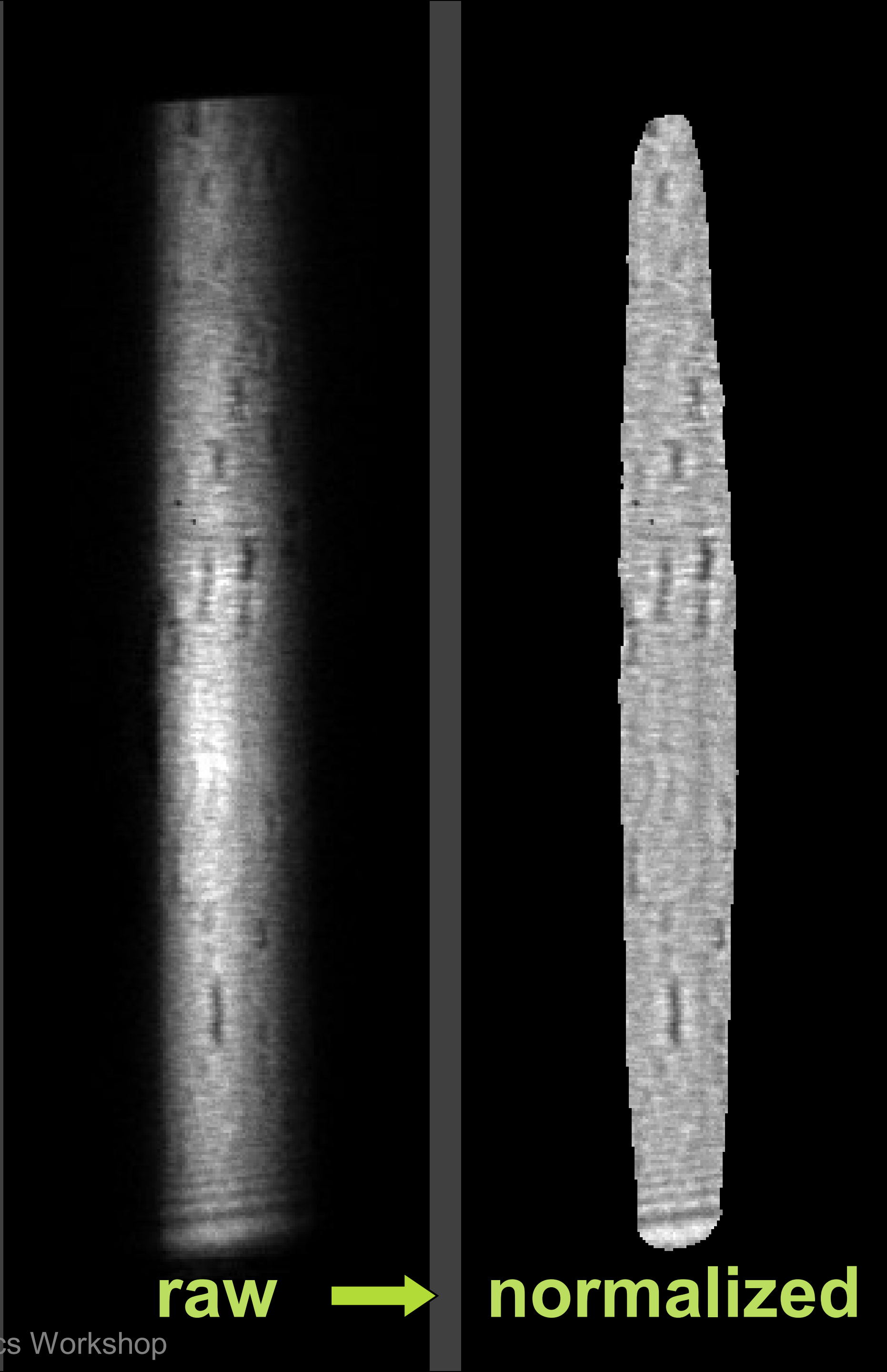
close to focus



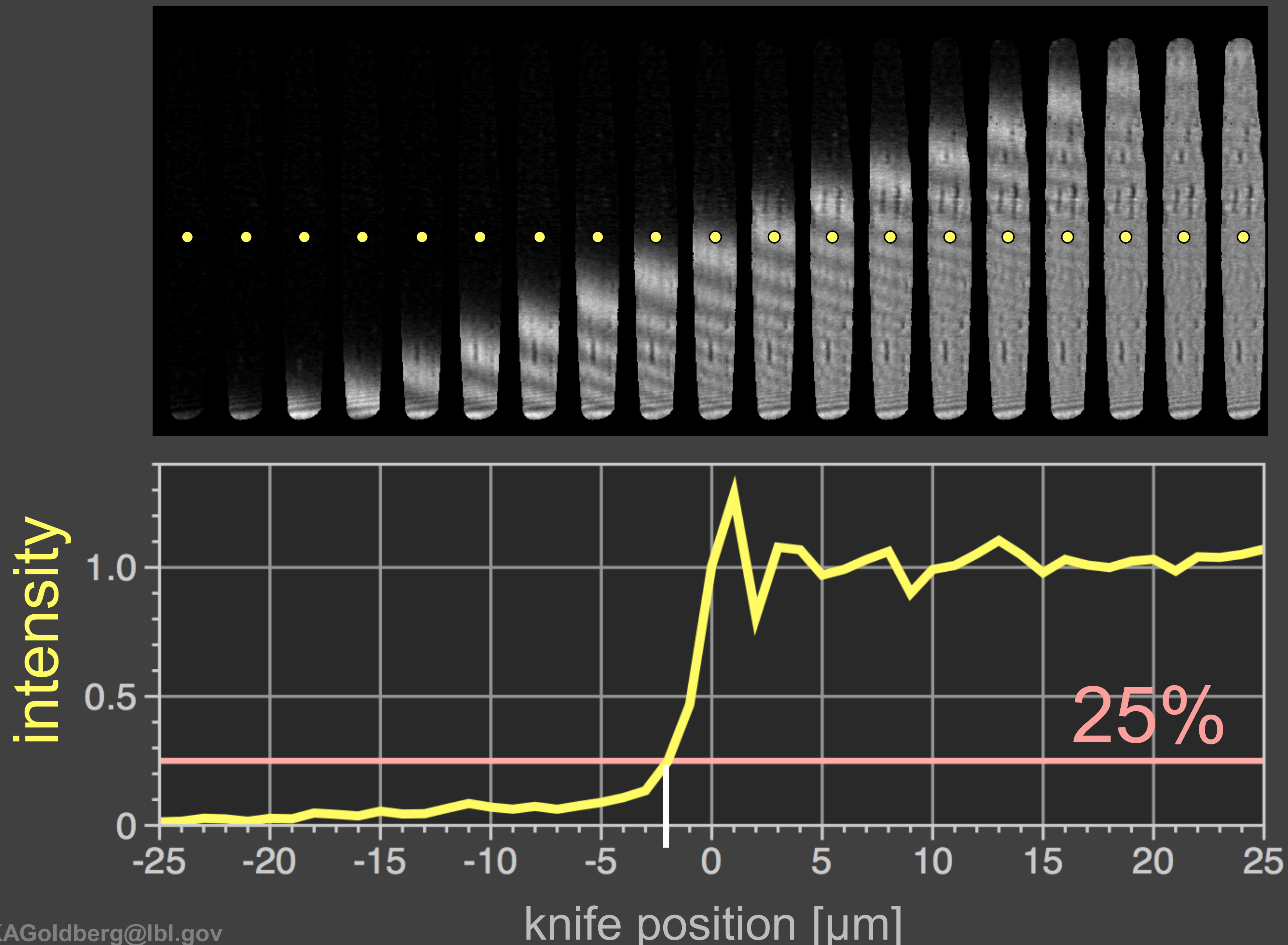
100721_0019

# Quantitative Knife-Edge Testing

*Must normalize the pupil. . .*

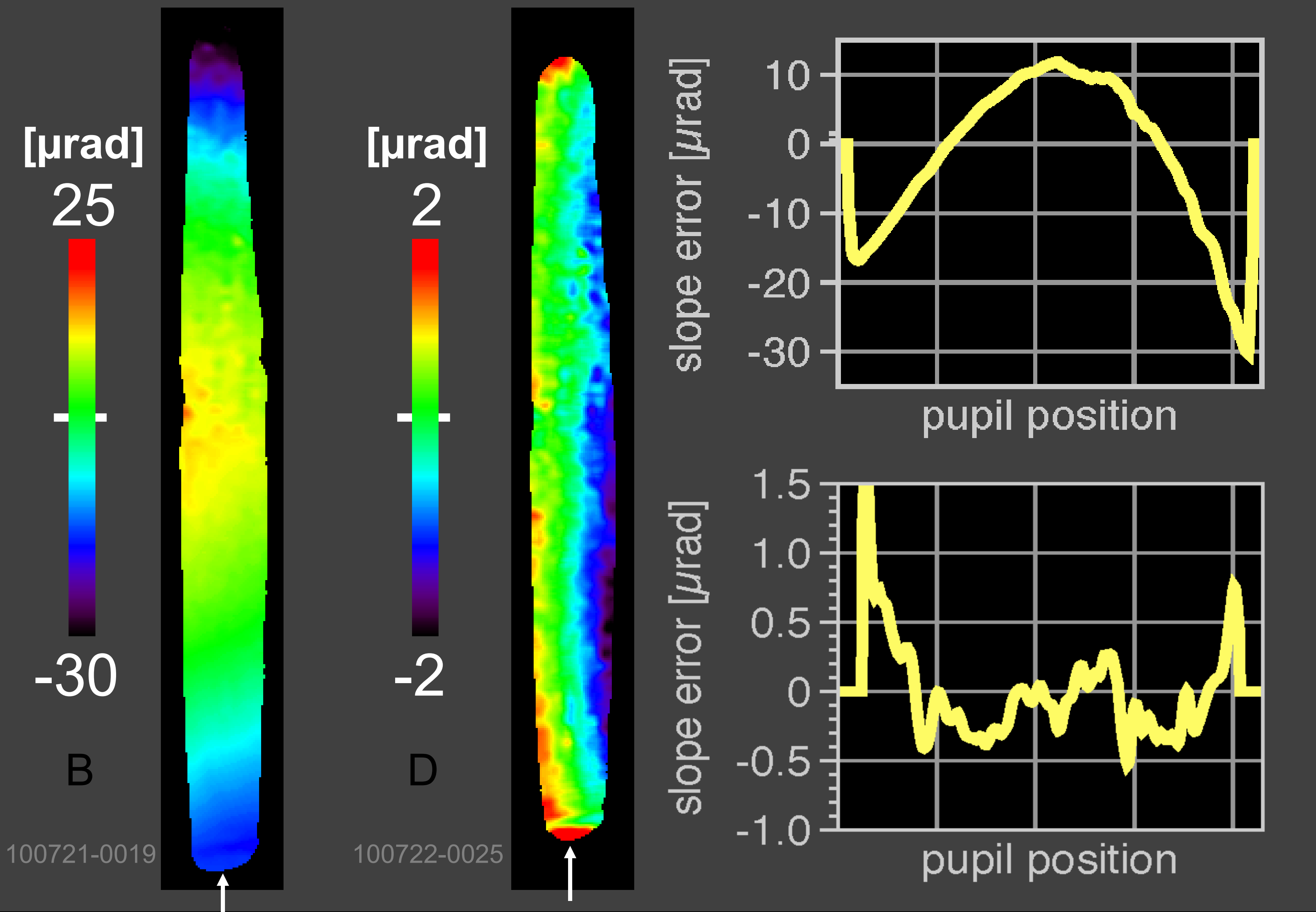


# **Knife Edge Scans:** Extracting slope, point-by-point



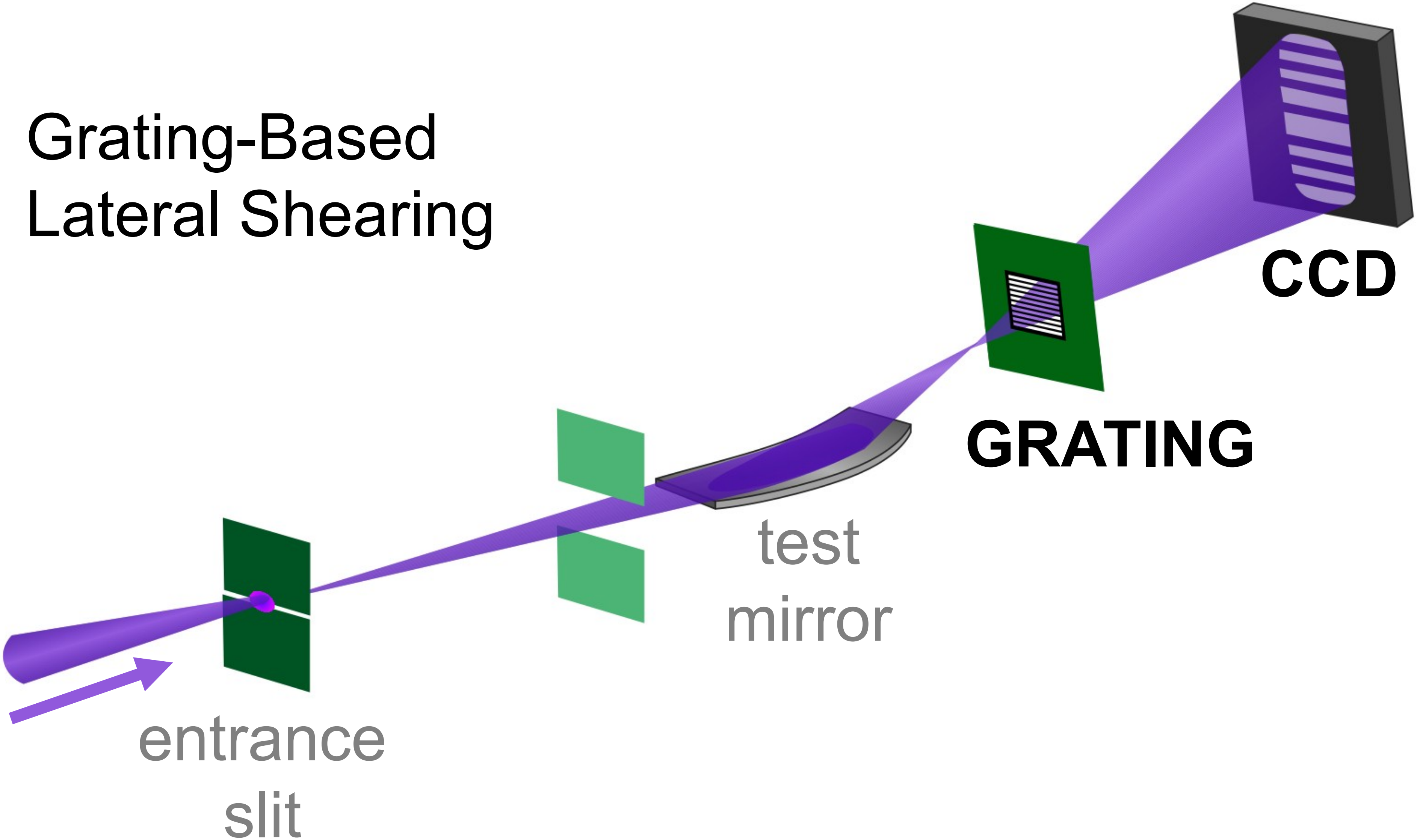

KAGoldberg@lbl.gov

# **Knife Edge:** Slope error calculations during alignment

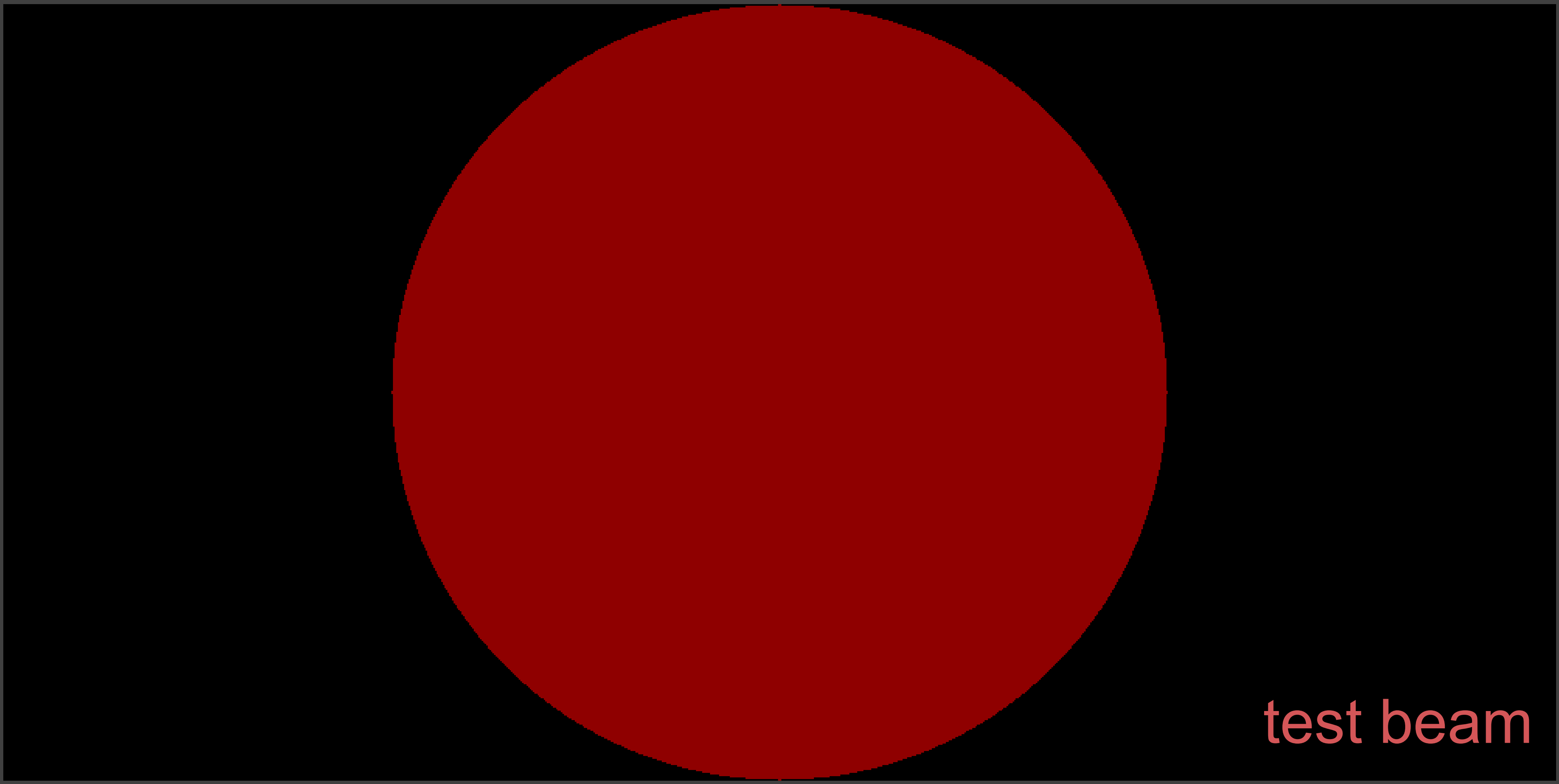


# At-wavelength testing strategies

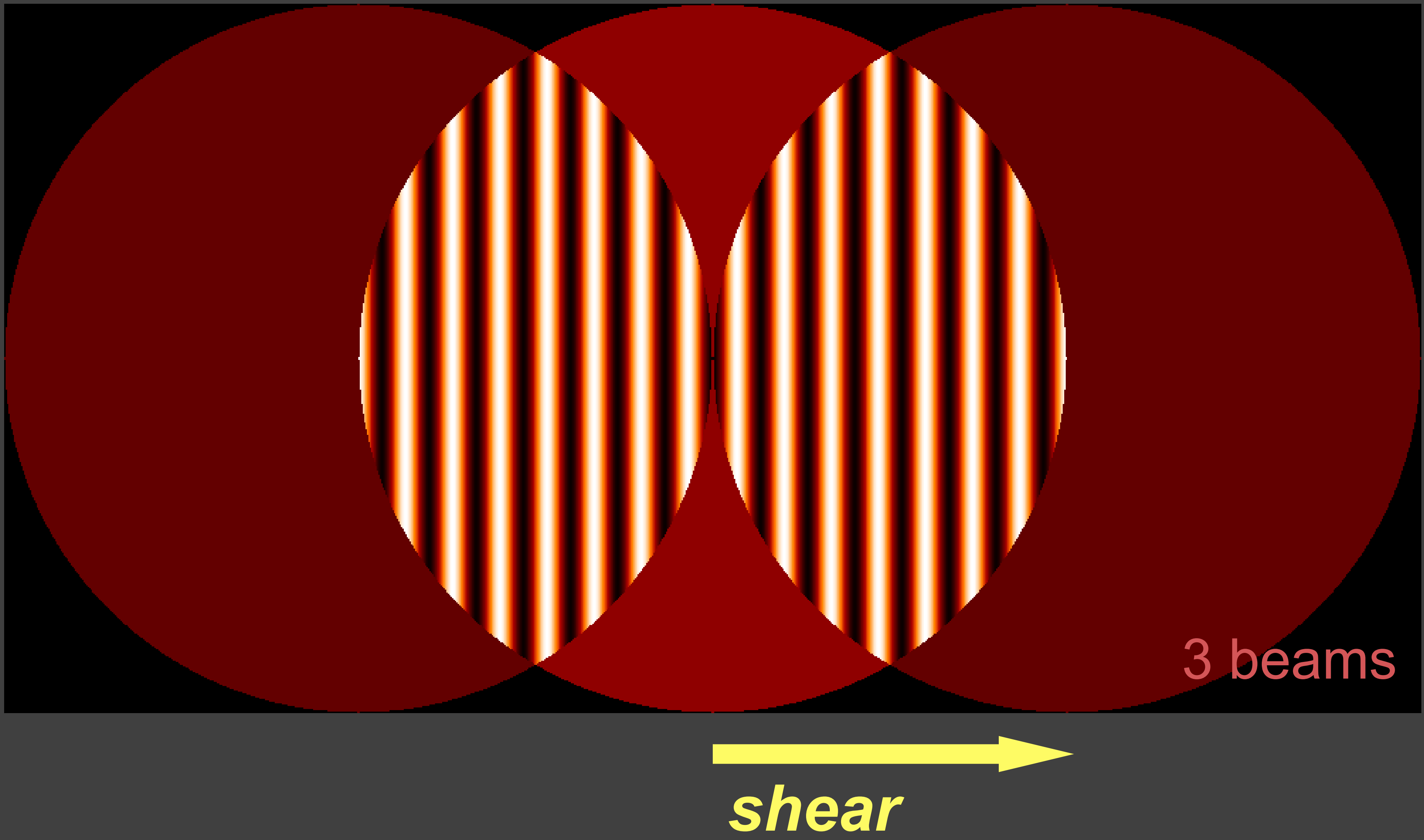
Grating-Based
Lateral Shearing



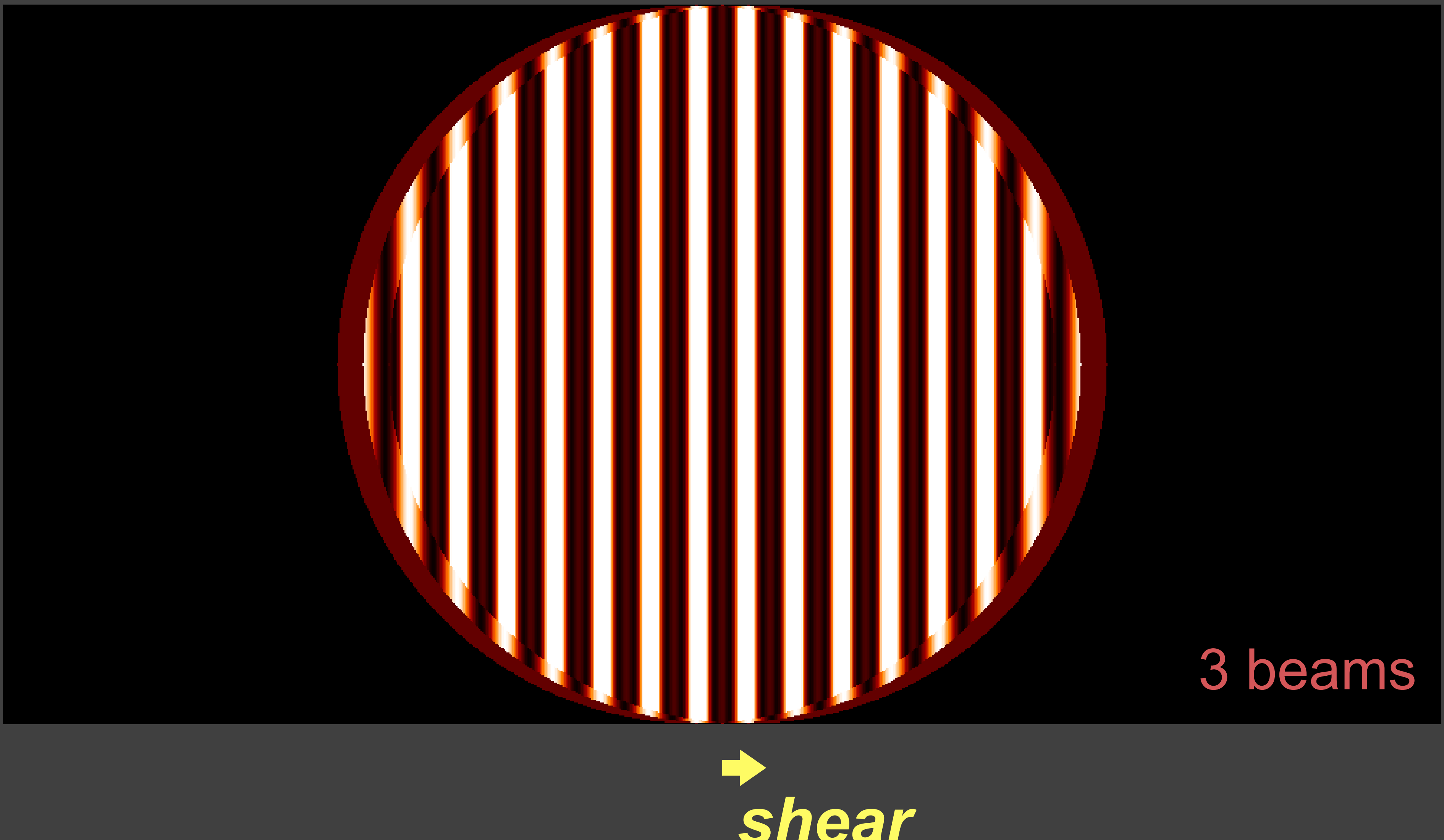
# Shearing: Conventional Description



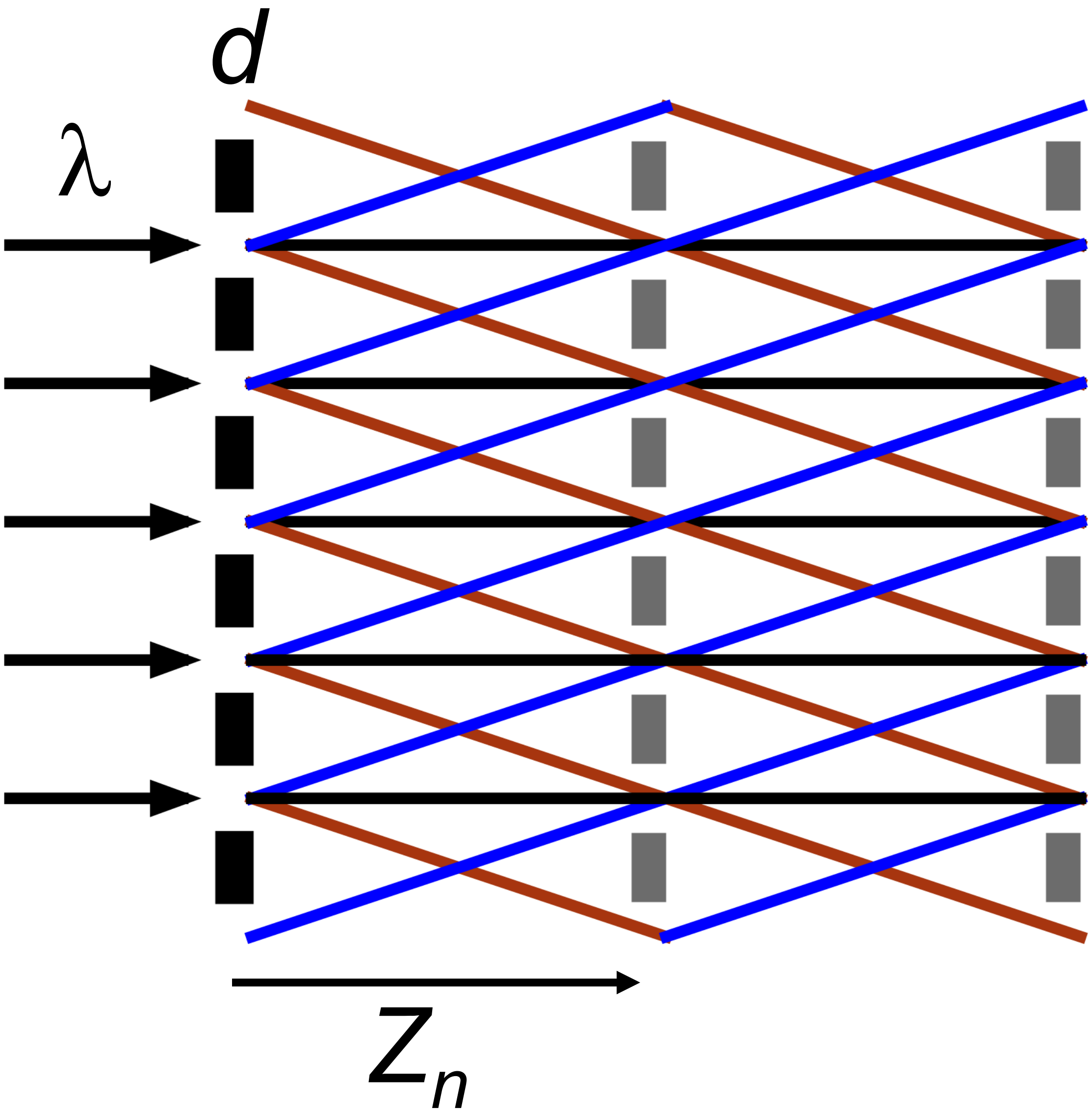
# Shearing: Conventional Description



# Shearing: *Small shear, high overlap*



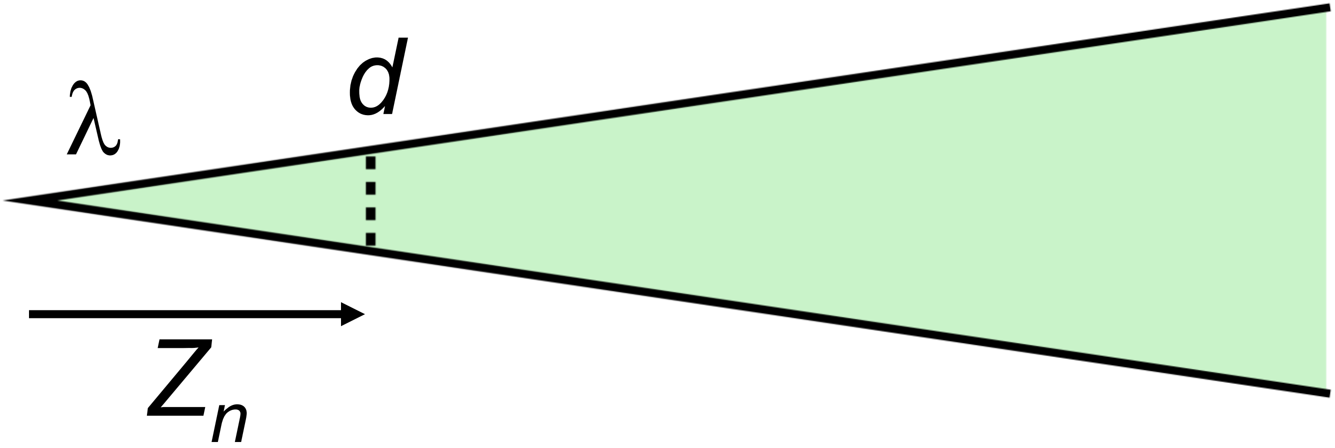
# **Talbot self-imaging effect:** *plane-wave case*




$$z_n = \frac{nd^2}{\lambda}$$

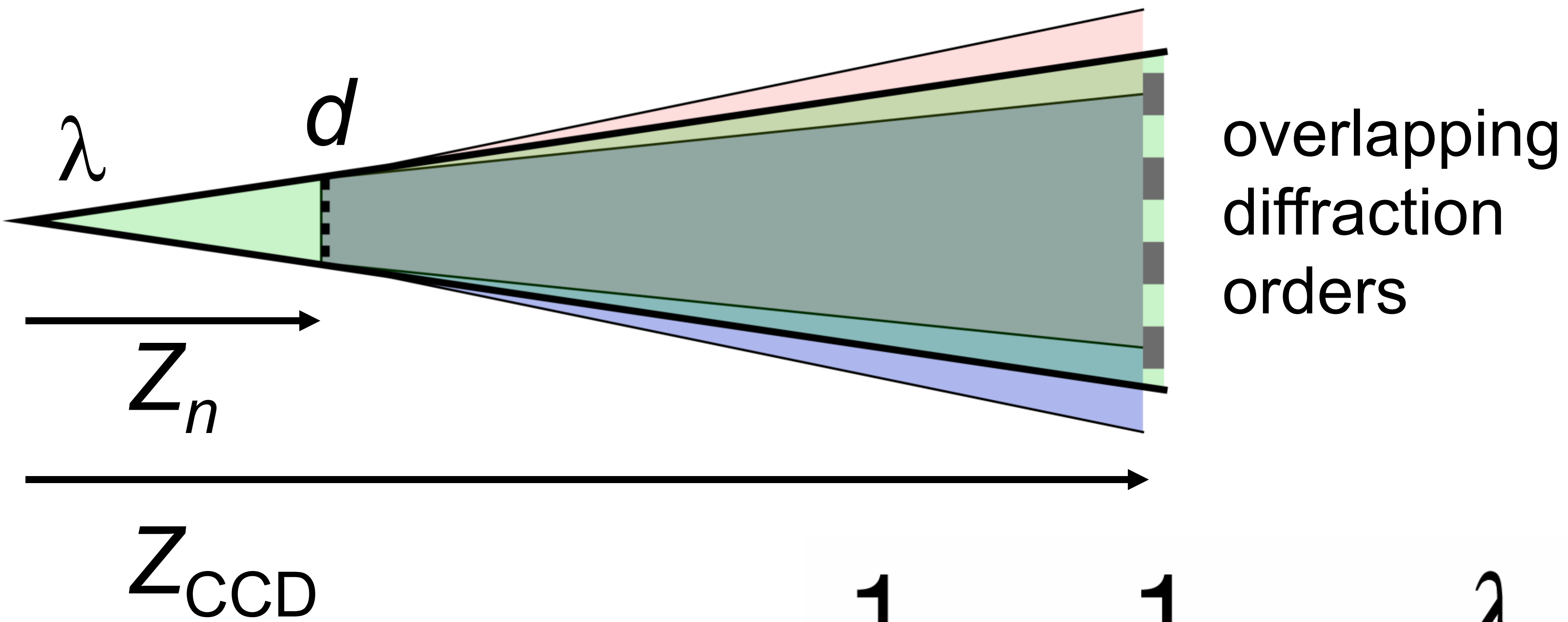
$$\frac{1}{z_n} = \frac{\lambda}{nd^2}$$

# **Talbot self-imaging effect:** *diverging-wave case*



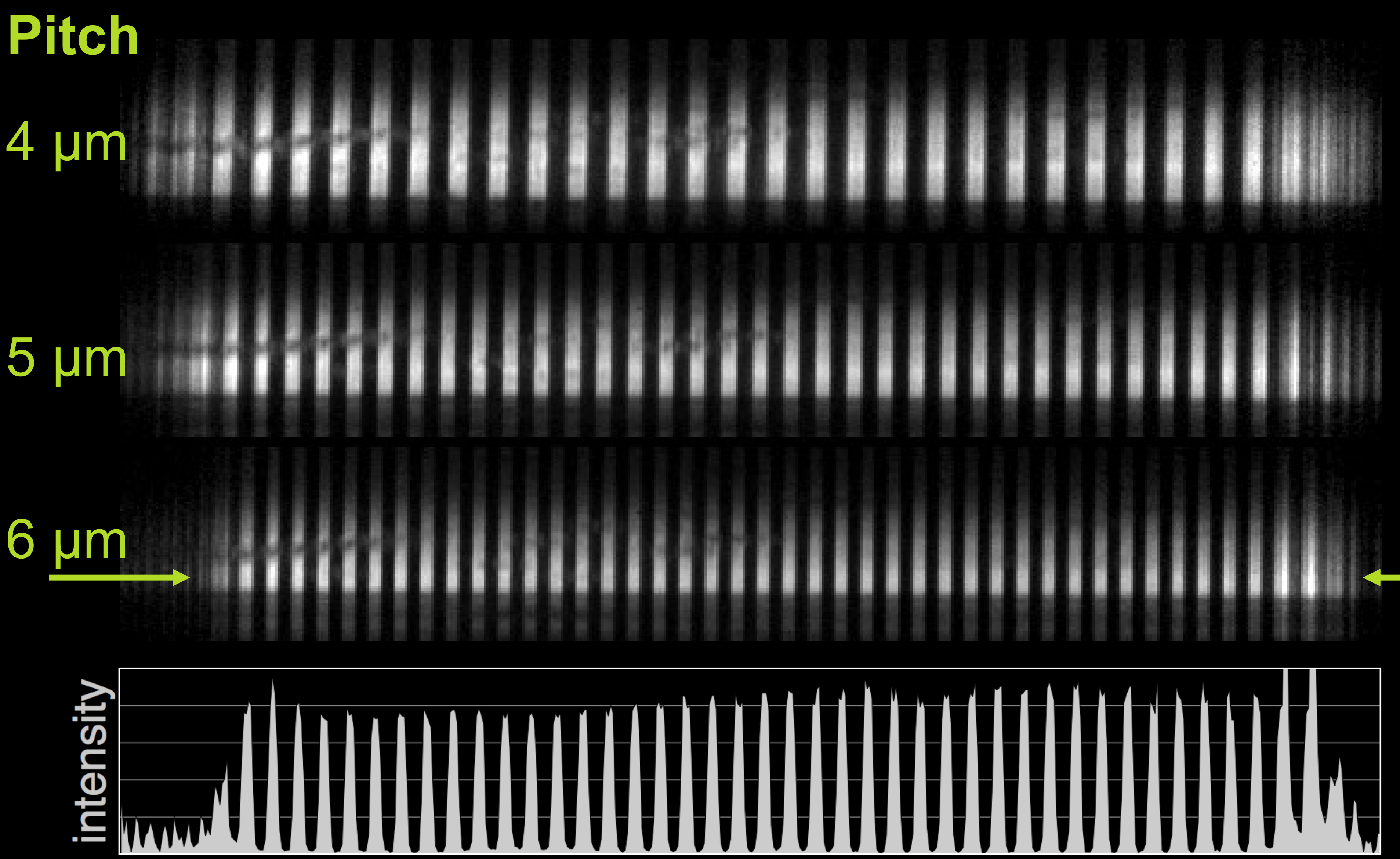
# Talbot self-imaging effect: *diverging-wave case*

# grating lines = # fringes on CCD

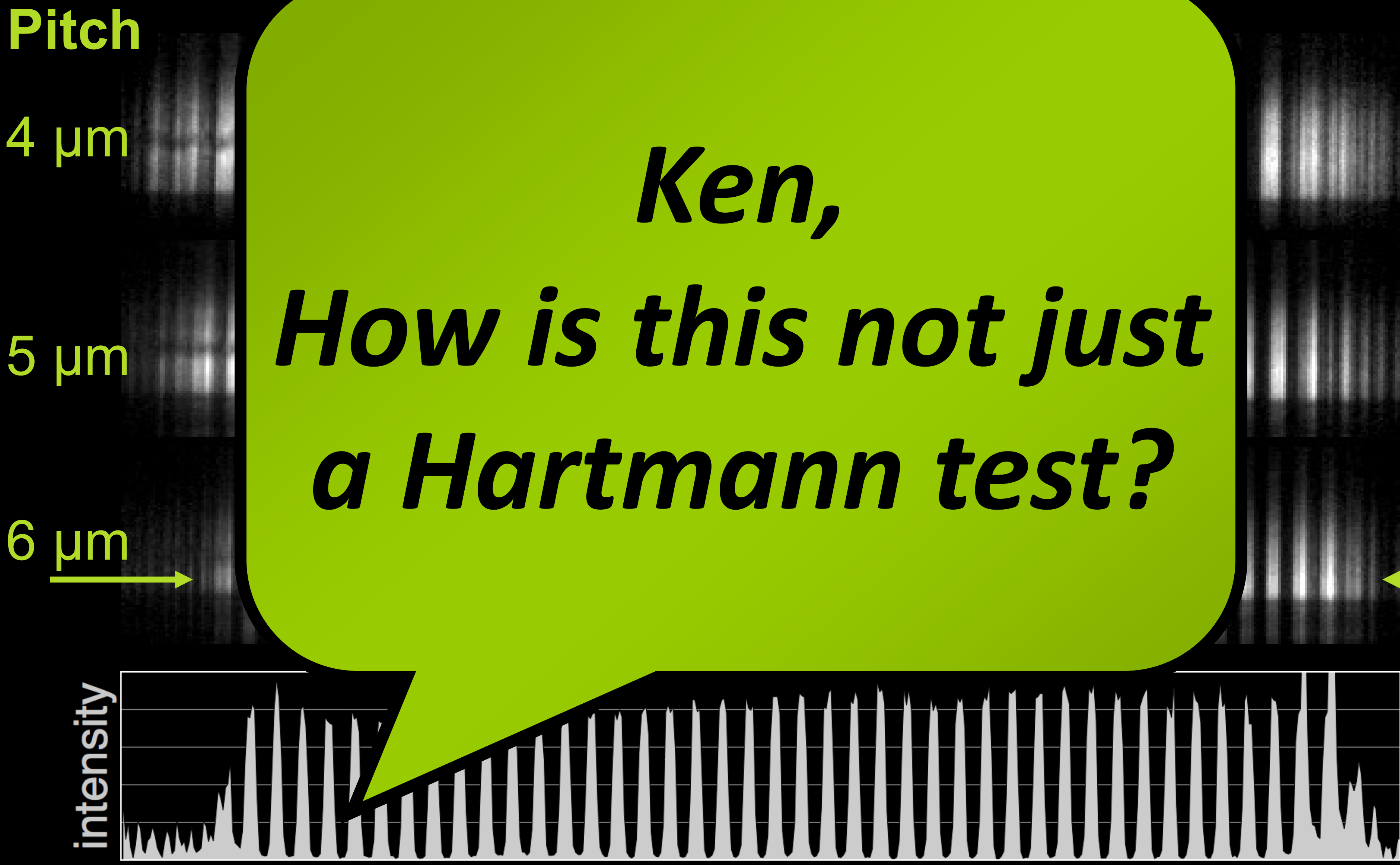



$$\frac{1}{z_n} + \frac{1}{z_{CCD}} = \frac{\lambda}{nd^2}$$

# **Shearing:** High fringe contrast



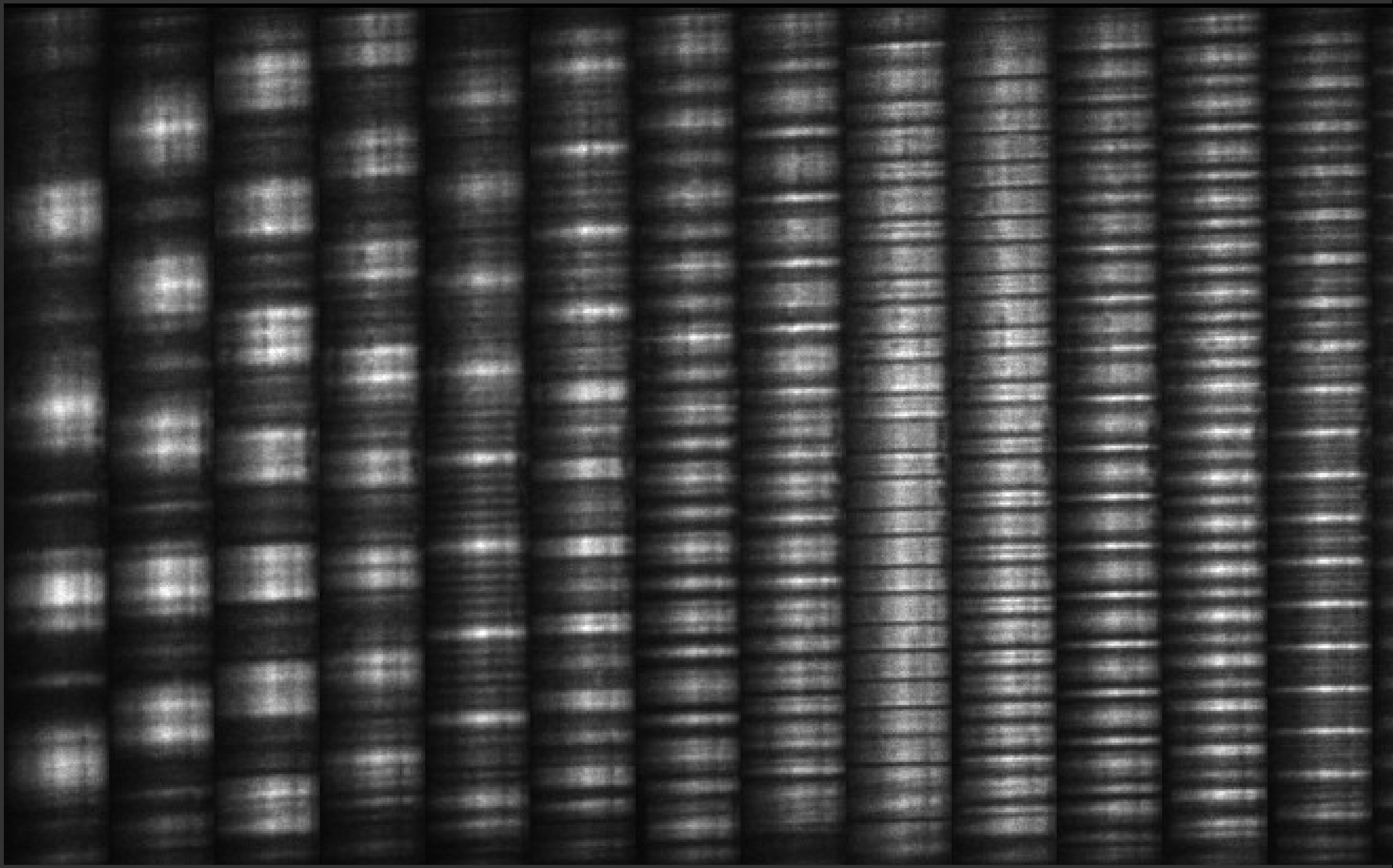
# **Shearing:** High fringe contrast




***Ken,***
***How is this not just a Hartmann test?***

KAGoldberg@lbl.gov

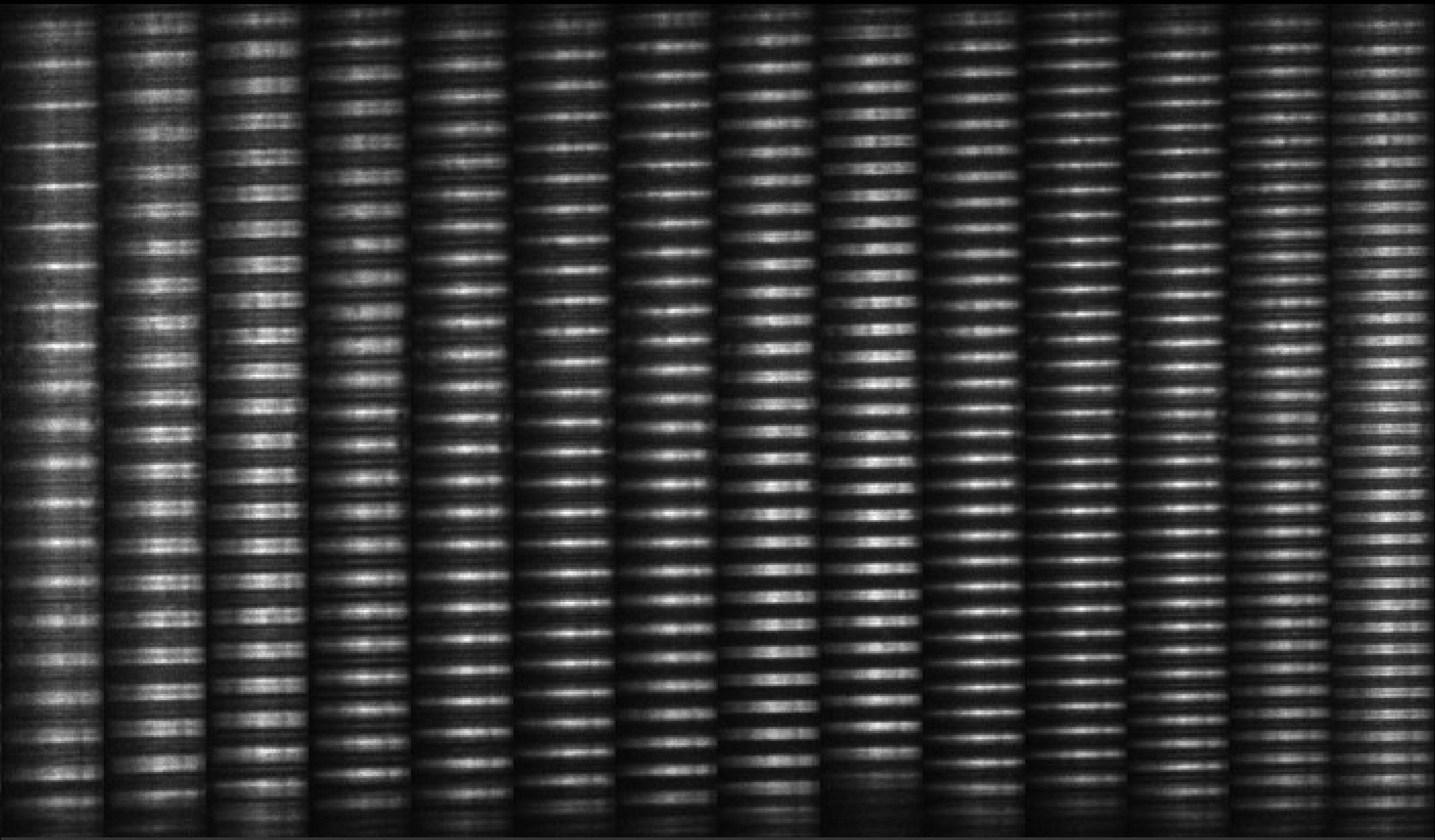
# Talbot effect: Interference of coherent waves



**grating position 1-mm steps** →

2010_07_29_5um

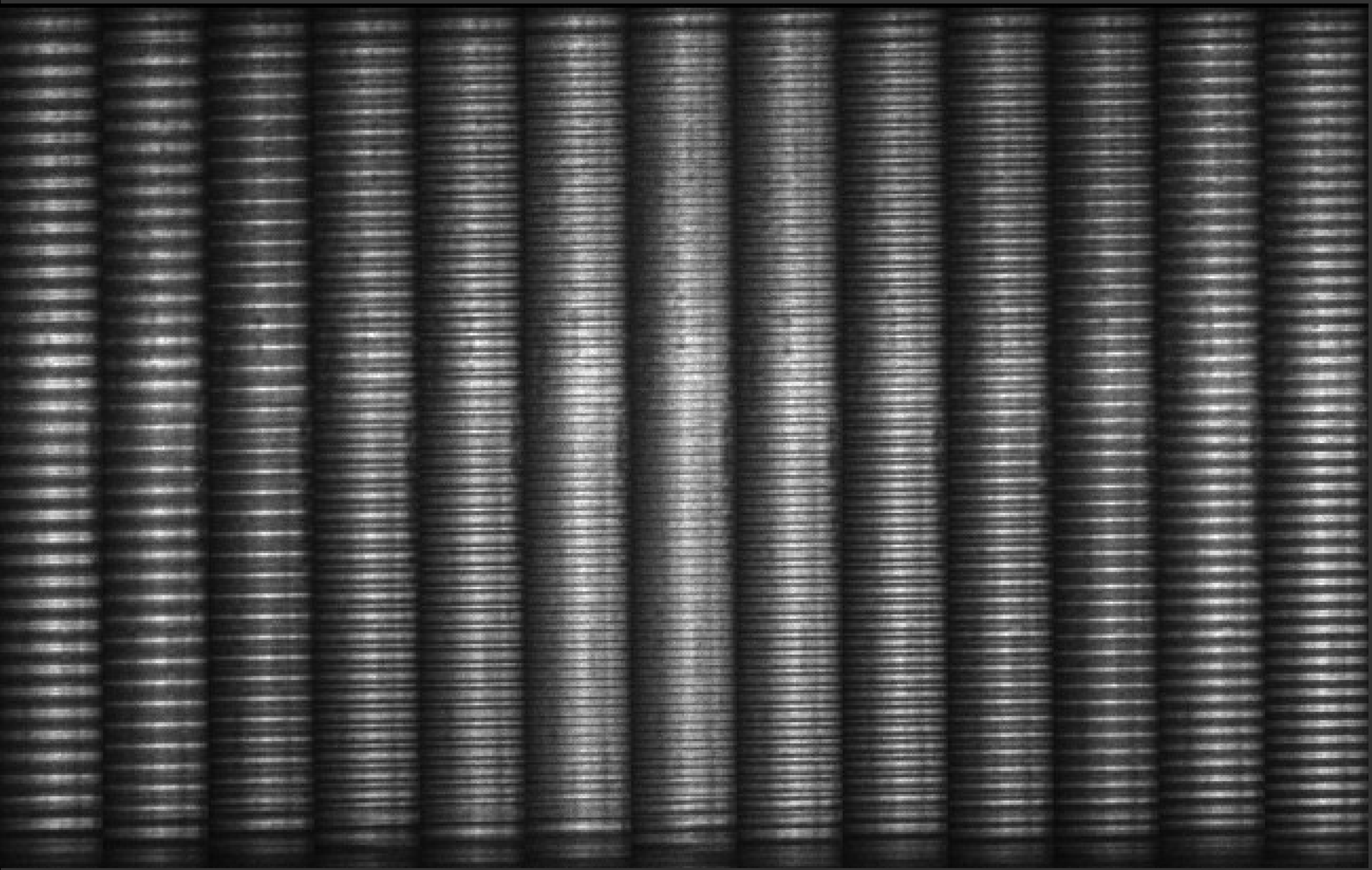
# **Talbot effect:** Interference of coherent waves



**grating position 1-mm steps** →

2010_07_29_5um

# Talbot effect: Interference of coherent waves



grating position 1-mm steps →

2010_07_29_5um

# **Shearing:** a few equations

$$W'(x) \approx \frac{W(x+s/2) - W(x-s/2)}{s}$$

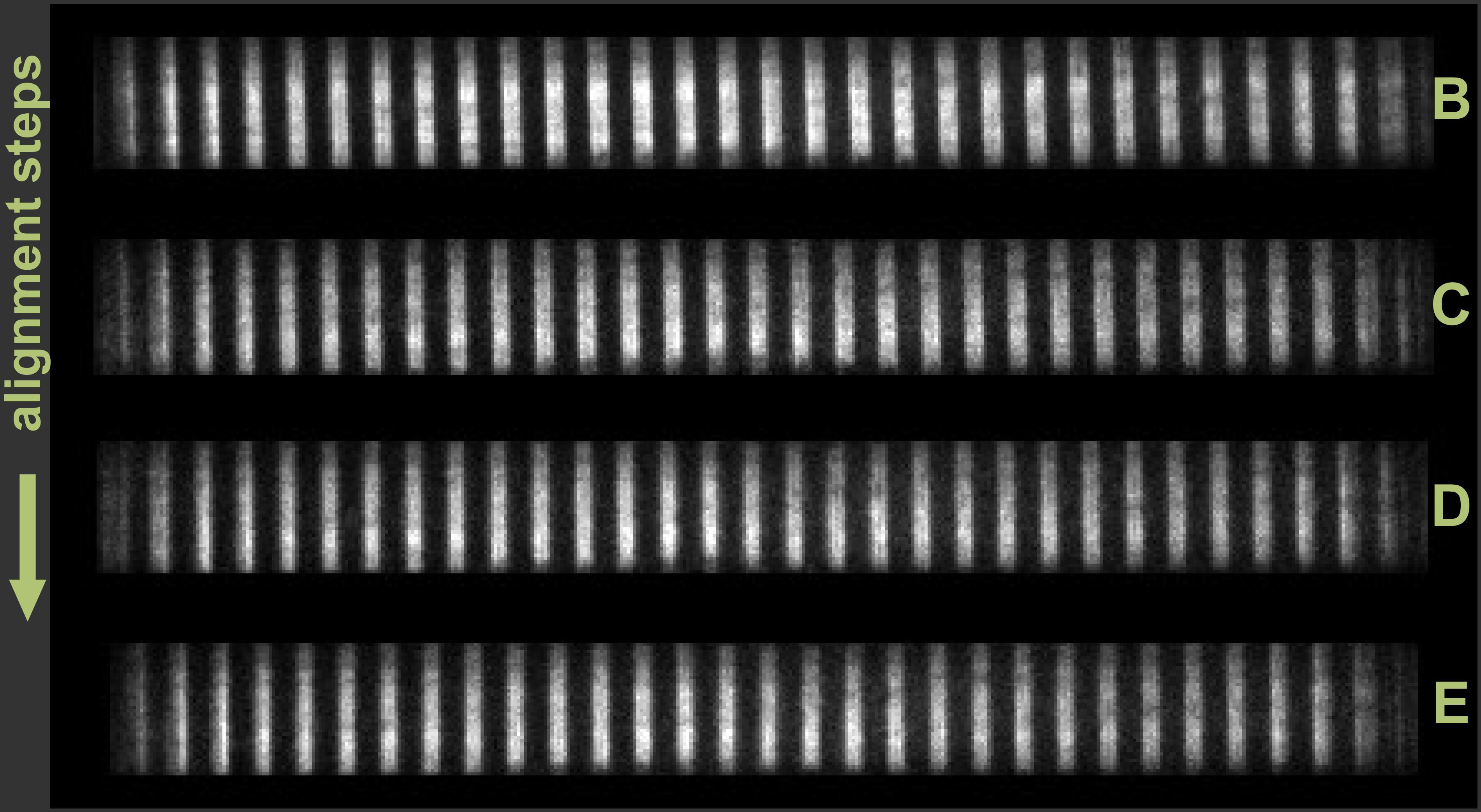
$$W'(x) \approx \frac{\lambda}{2\pi s}\phi_{Measured}(x)$$

$$s = z\frac{\lambda}{d}, \quad \text{where } z \equiv z_{CCD} - z_g$$

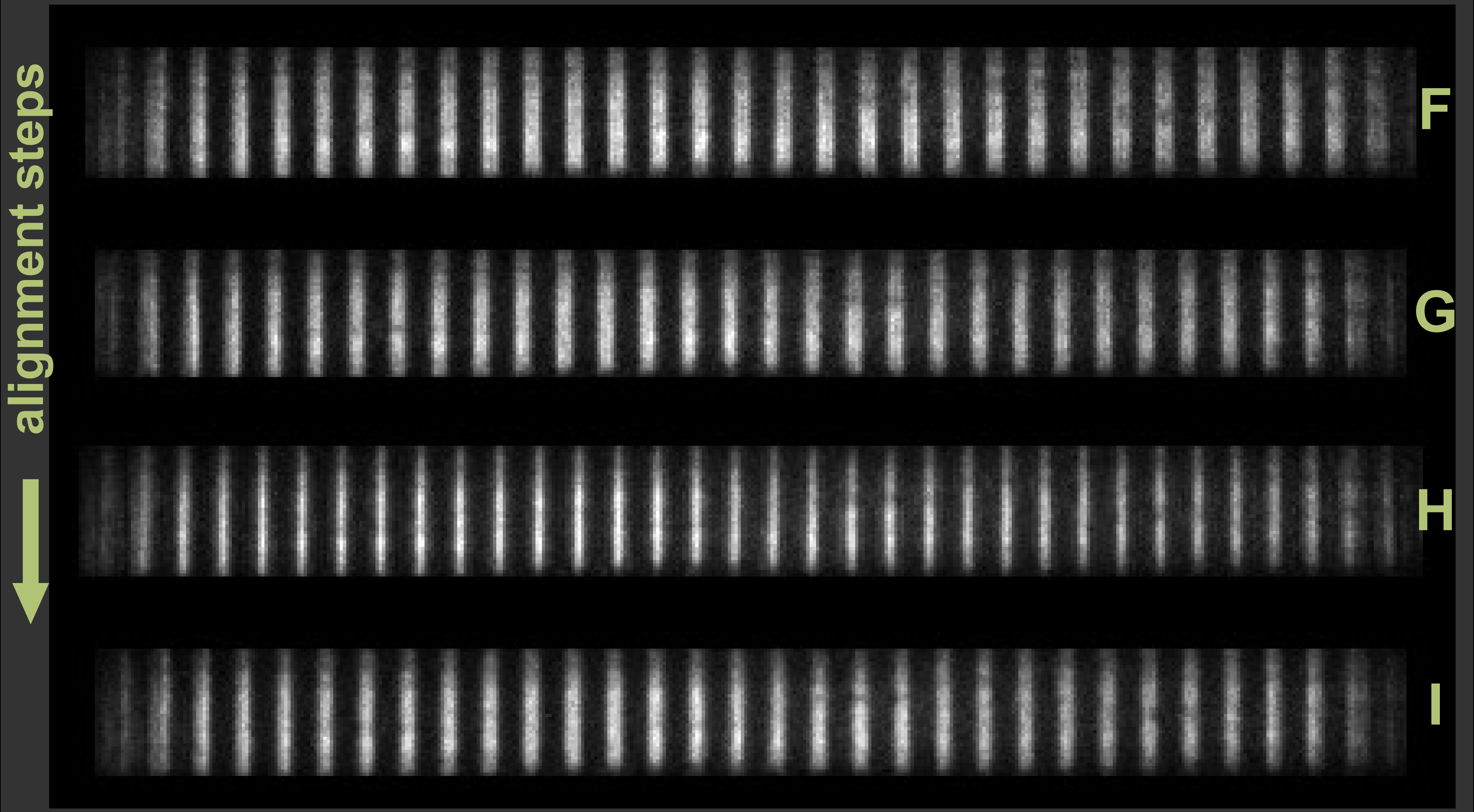
$$\mathbf{W'(x) \approx \frac{d}{2\pi z}\phi_{Measured}(x)}$$

$(d\,/\,2\pi z)\downarrow$
sensitivity$\uparrow$

# Mirror fine alignment with shearing

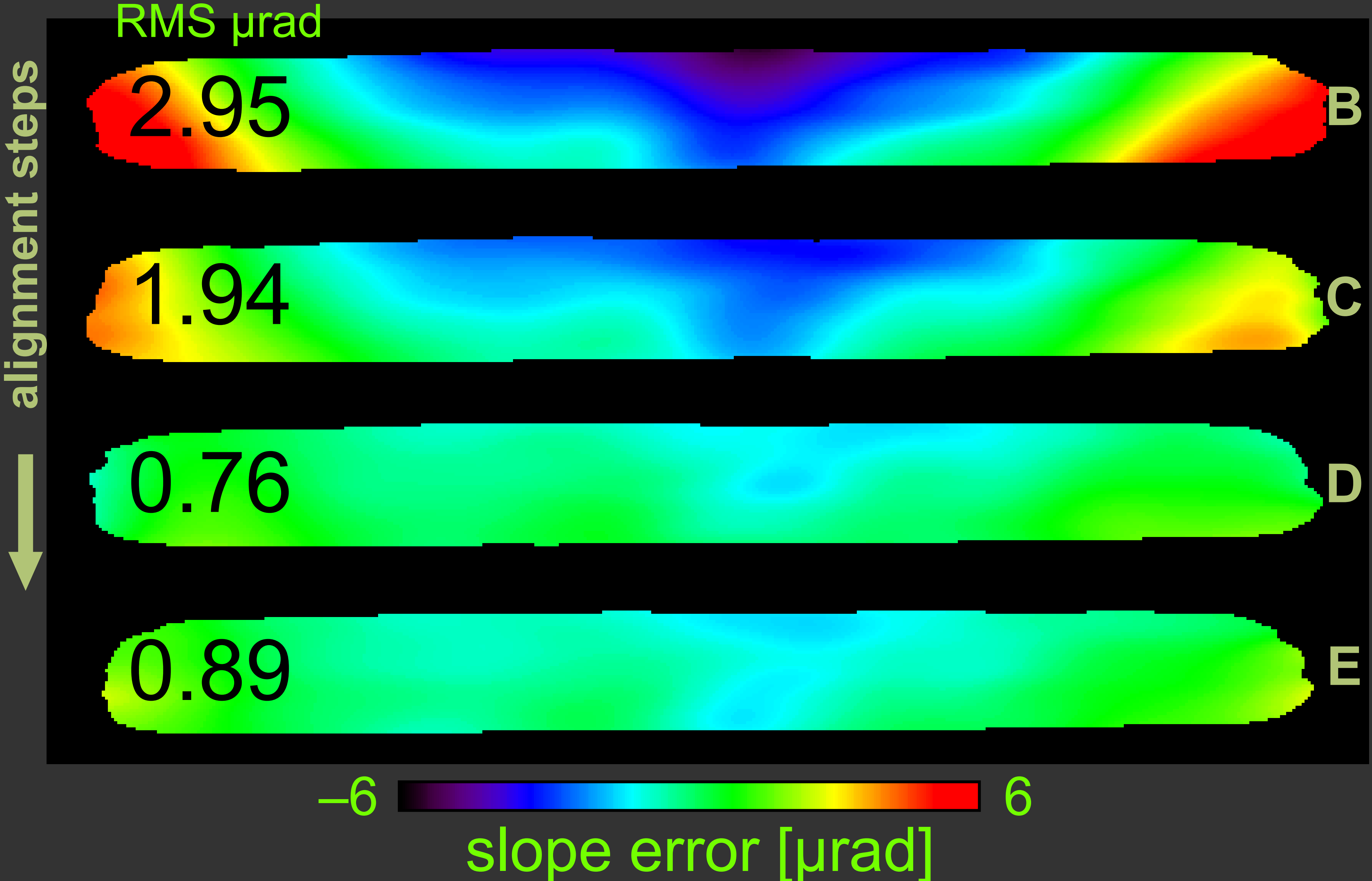


# Mirror fine alignment with shearing



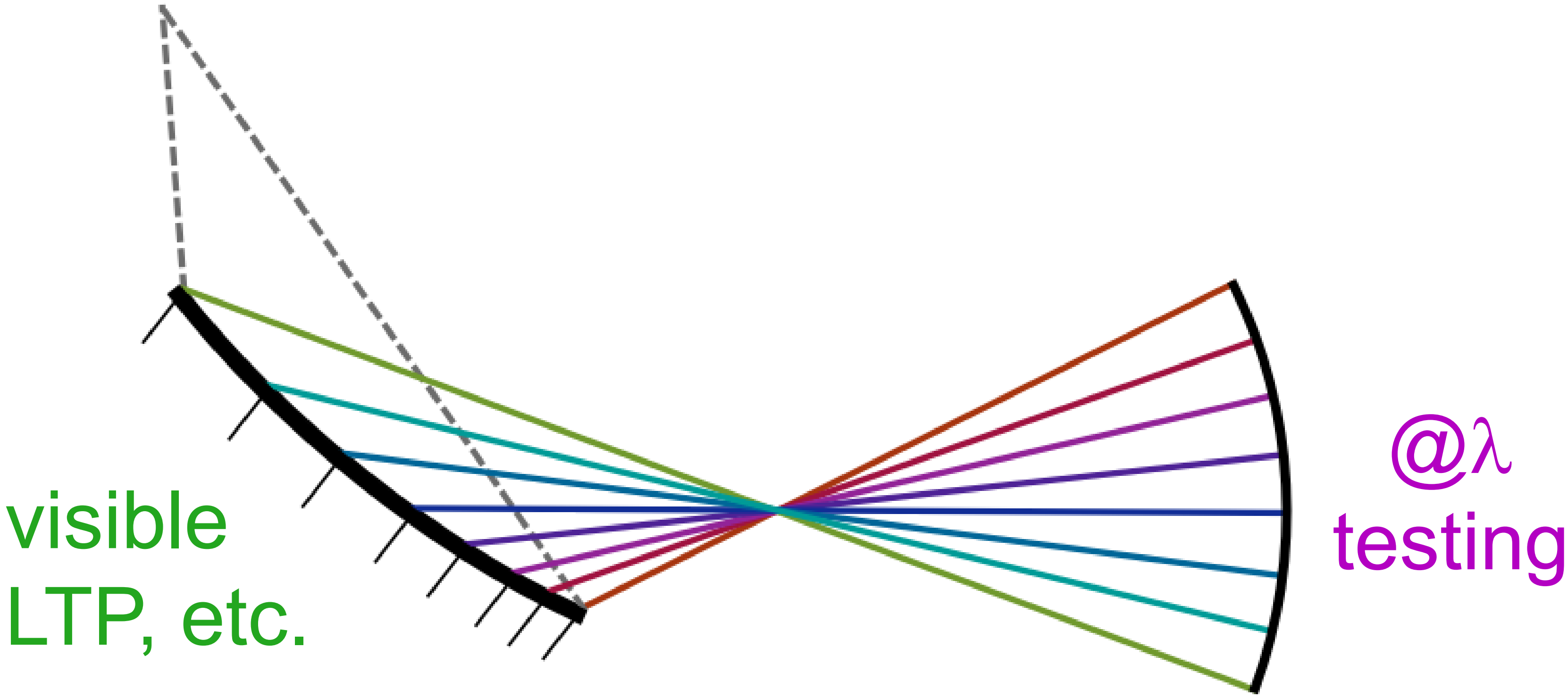

*Analyze with the Fourier-Transform method. . .*

# Mirror fine alignment with shearing



# Mirror fine alignment with shearing

# Mapping wavefront slope measurements onto the mirror surface




1. Non-linear mapping CCD(x) to mirror(x)
2. Scaling of the slope magnitude vs. z

# At-wavelength testing strategies: Summary

| | | |
|---|---|---|
| **Upstream scanning slit** *on YAG* | Very easy<br>In focus, it's exact | Low resolution<br>Relatively slow |
| **Upstream scanning slit** *on CCD* | More sensitive | Must calibrate the systematic error<br>Relatively slow |
| **Downstream scanning slit** | Like Hartmann | Relatively slow |

# At-wavelength testing strategies: Summary

| | | |
|---|---|---|
| **Knife-Edge** w/ photodiode | Find beam size | But no WF w/o *Fineup* |
| **grating-based Shearing** | Fast, easy, variable sensitivity<br><br>Loses info at edges | Low-spatial frequencies |
| **Hartmann** | Proven, easy, *commercial* | Can it take us to 50 nrad? |
| double-grating (a.k.a. *Talbot*) | Good for hard x-ray | Not necessary for soft x-ray? |

# At-wavelength testing strategies: *Next Steps*

In situ **bending** and optimization

Detailed cross comparisons

*scanning slits, knife-edge, shearing, (Hartmann)*

Comparison with LTP

2-D KB focusing tests

**Transfer to other beamlines**

# *Thank you!*

Special thanks to **Patrick Naulleau, Howard Padmore**

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