Structure in out-of-focus beams of X-ray focusing mirrors: Causes and possible solutions

John Sutter, Simon Alcock, Kawal Sawhney
Diamond Light Source Ltd

Fiona Rust
Department of Physics, University of Bath

Grazing-incidence mirrors are standard optics
for focusing X-ray beams at synchrotron beamlines.

Bimorph mirrors widely used at DLS:
- range of focal distances
- correction of long-range slope errors (period ≥ 2×electrode interval)

But some users prefer out-of-focus X-ray beam on sample:
- reduces rate of radiation damage
- relaxes tolerance of sample position
- provides uniform intensity over whole sample

Methods for defocusing X-ray beam to specified size at sample:
- addition of uniform curvature to mirror figure (DLS)
- calculation of mirror figure adjustment optimised to incident intensity (D. Spiga et al, *Nucl. Instrum. Meth. Phys. Res. A* **710**, 125-130 (2013)).

diamond

Multi-peak structures in defocused beam: problem for sample

- increased radiation damage at “hot spots”
- variable radiation exposure while sample is rotated

Beam structure visible even from bimorph mirrors polished to state-of-the-art levels (≤ 0.5 μrad rms)

→ acceptable slope errors for focusing do not necessarily yield acceptably uniform defocused beam!

We will consider the following using measurements done at Diamond:

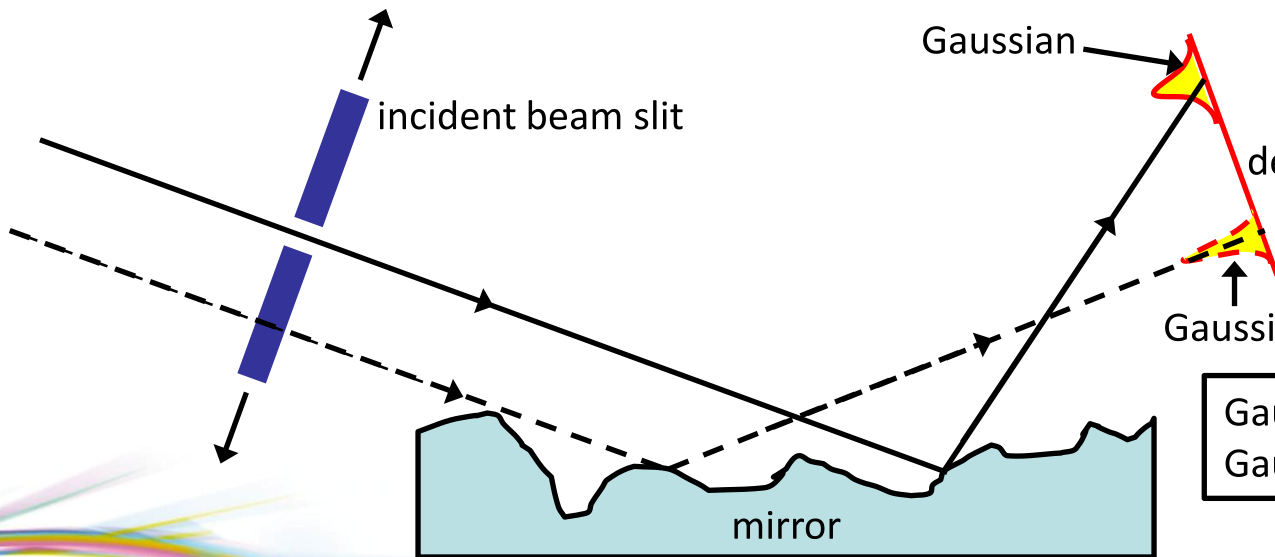
- **Can mirror slope errors be related to defocused beam structure?**
- **How carefully must mirror slope errors be controlled?**
- **How might mirror polishing errors be specified – is rms enough?**
- **How might future mirrors be designed for smooth defocusing?**

diamond

Calculation of defocused beam profile from measured slope errors:

Test case: Diamond I02 vertical focusing mirror after repolishing
600 mm long, 8 electrodes, 33.115 m from source, 6.885 m to sample,
2.7 mrad grazing incidence at center

Measurements collected by in-situ pencil-beam scans:



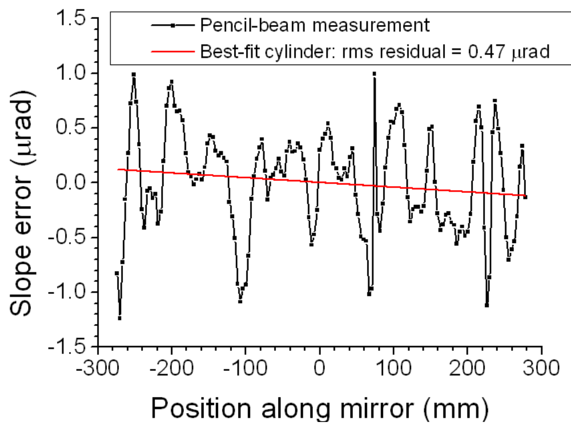
Gaussian width = slit width
Gaussian area = measured area

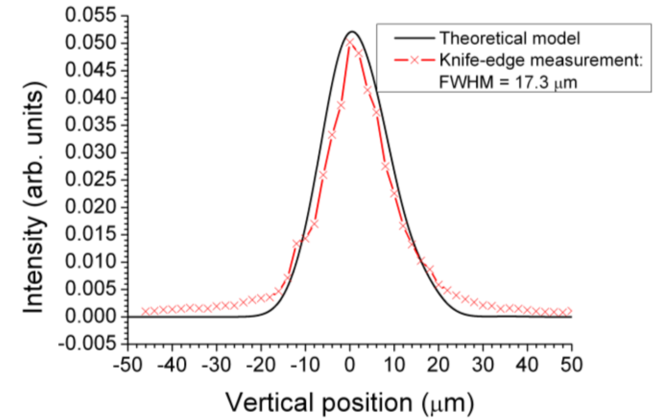
Each slit position produces a Gaussian on the detector.
Σ (all Gaussians) = theoretical profile.

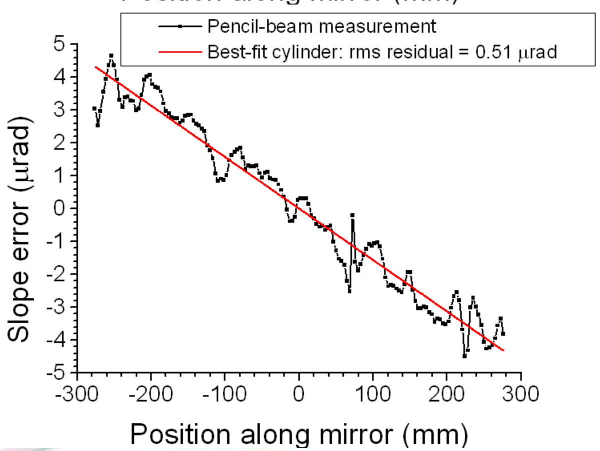
No interpolation is needed.

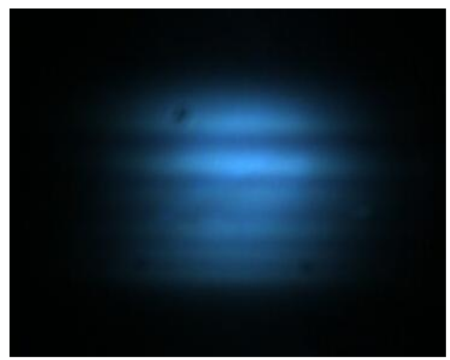
diamond

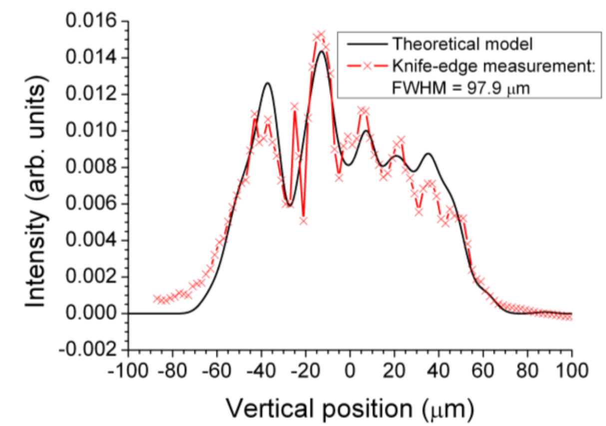
Comparison of theoretical profiles to beam images and knife-edge scans:

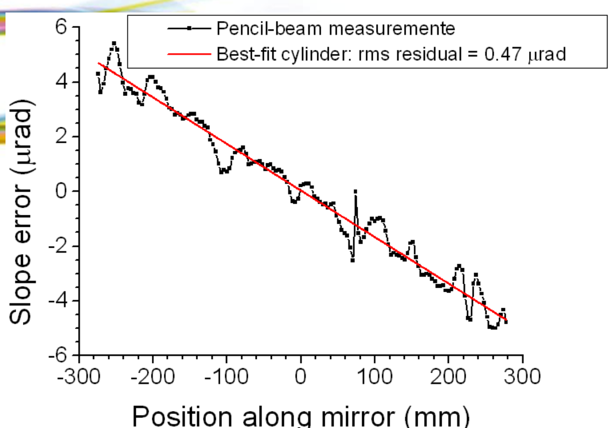


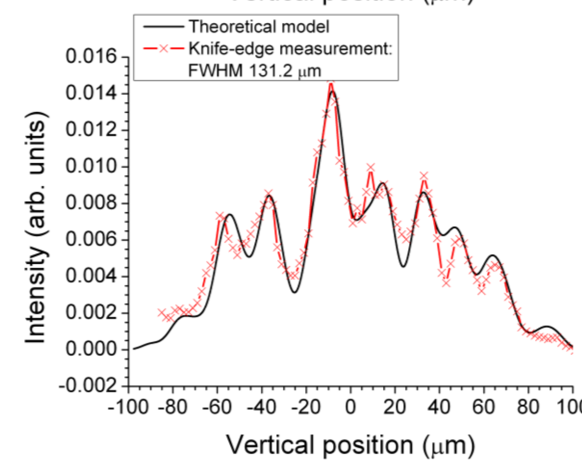












Good agreement between theoretical and measured profiles

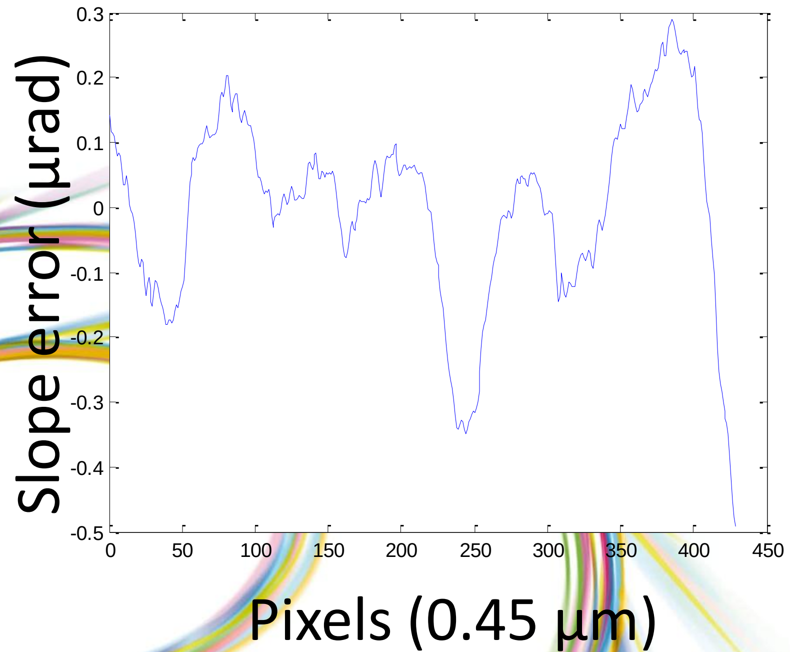
→ We can estimate defocused beam profiles from known slope errors.

→ 0.5 μrad rms slope errors can cause significant structure!

<u>Test case</u>: super-polished EEM (elastic emission machining) bimorph mirror at B16 (Thales-SESO & JTEC Corporation, Japan):

150 mm long, 8 electrodes, 46.5 m from source, 0.4 m to sample

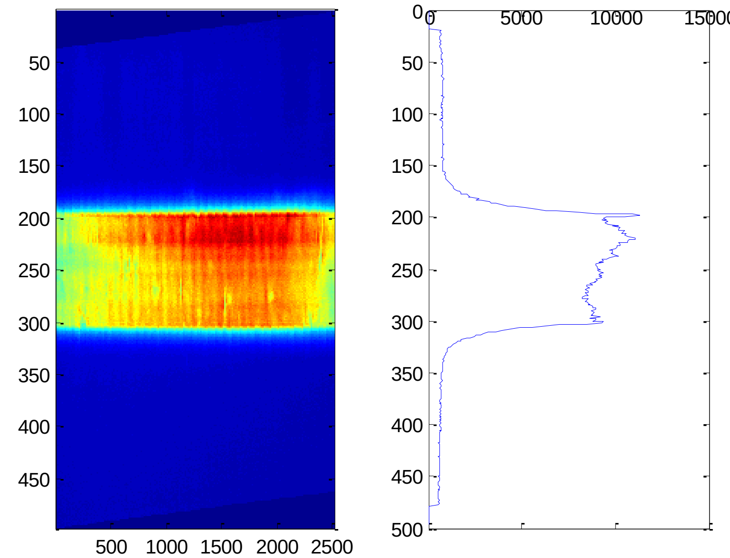
Optimisation using speckle measurements of wavefront error (Hongchang Wang & Sébastien Berujon, this workshop) yielded



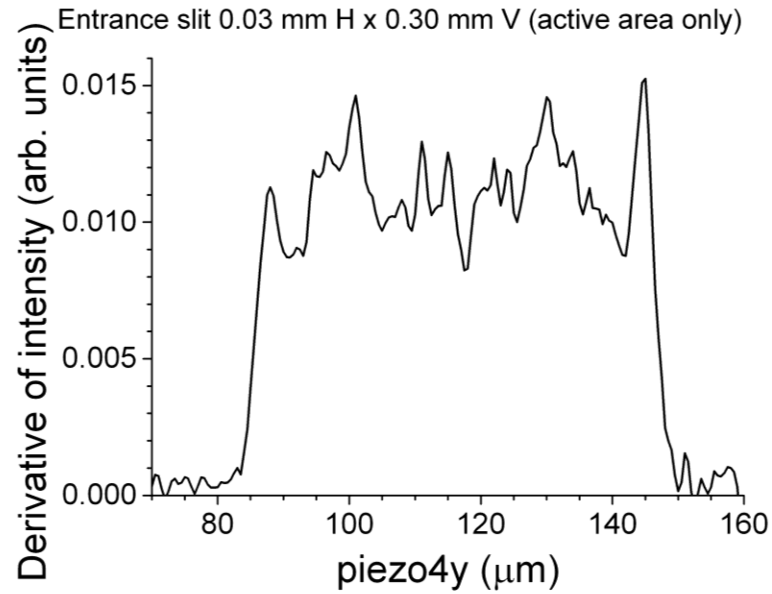
Minimum rms slope error = 0.1457 μrad

Best-fit radius of wavefront = 3221.77+/-6.9043 mm

Camera image (0.45 µm/pixel) after refinement of voltages with speckle method:



3-point smoothed derivative of knife-edge scans:



Defocused beam structure is not severe but still present.
Note that knife-edge scan reveals fine structure that camera's point-spread function smears out.

Very tight control of slope errors (< 0.15 µrad) appears necessary to remove all structures in defocused beams.

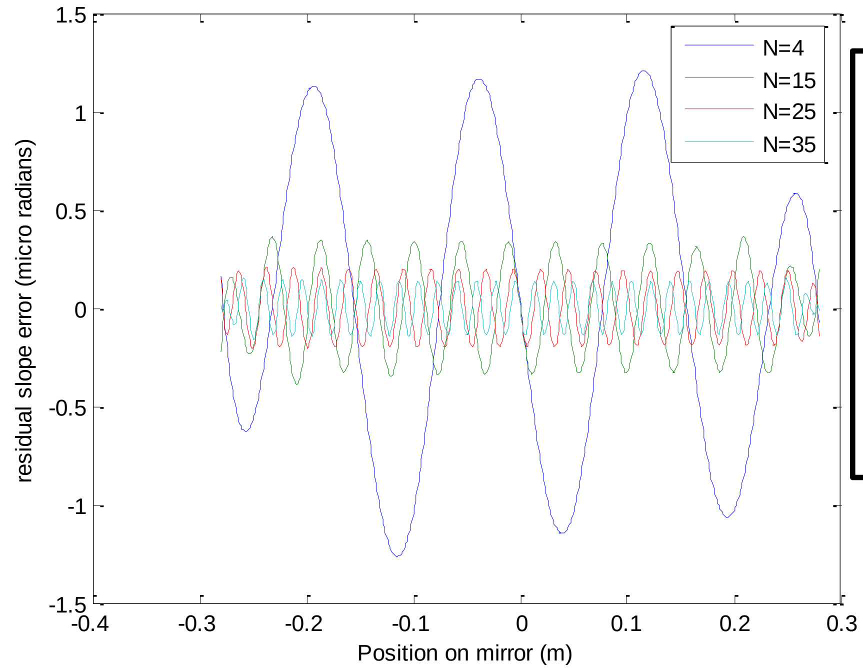
Can we specify types and amounts of slope errors that cause especially good – or bad – structure?

Let x = coordinate along the mirror's length (x=0 is center of mirror).
X = coordinate along detector screen (X = 0 is center of beam spot).

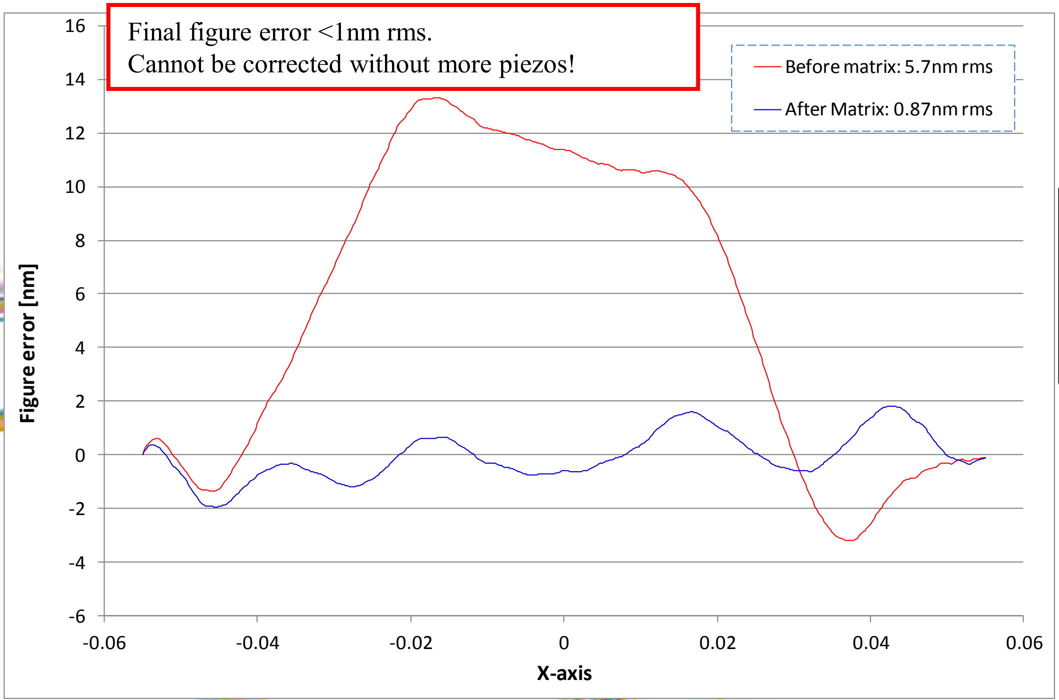
We start with the simplest possible model:

Mirror slope deviation $S(x)$ = a single sine wave + a straight line

- Sine wave:
  Models of bimorph mirror elliptical bending show oscillating residual slope errors (period ~ interval of electrodes)
- Straight line:
  Approximates uniform overall curvature added for defocusing.



Simulated bending of bimorph with *N* electrodes:
Model: discussed in next section
Original surface: flat
Final surface: ellipse as in I02 VFM
Mirror length *L*: 0.56 m
Electrode width: ½ (*L*/*N*)
Credit: Fiona Rust



Final figure error <1nm rms.
Cannot be corrected without more piezos!

Measured figure error of super-polished bimorph mirror on Diamond-NOM
Credit: Simon Alcock

diamond

In geometrical optics, the position of a ray on the detector is

$$X = 2(q+x)S(x)$$

but if the mirror's length << q, then to a good approximation

$$X = 2qS(x)$$

If local *curvature* error $C(x)$ at some region is 0, its reflected rays form sharp focus at detector.

But $C(x) = S'(x)$!
→ maxima and minima of mirror slope deviation cause "hot spots".

Measurements on a non-bimorph mirror (Diamond I20) confirm this:
Local curvature error at a specific region of the mirror
is proportional to width of beam reflected from that region at detector.

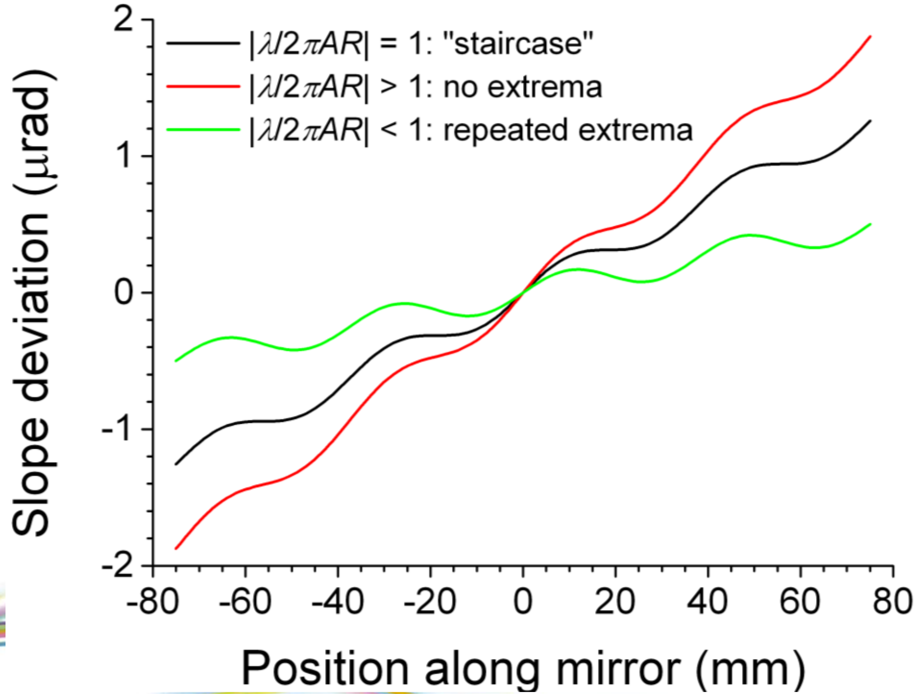
diamond

In our simple model,

$$S(x) = x/R + A \sin(\varphi + 2\pi x/\lambda)$$

Look for values of x at which $S'(x) = 0$:

these will form hot spots at detector



Best for avoiding hotspots:
$|\lambda/2\pi AR| \gg 1$

Worst hotspots:
$|\lambda/2\pi AR| = 1$
$S'' = 0$ at all points on mirror where $S' = 0$!

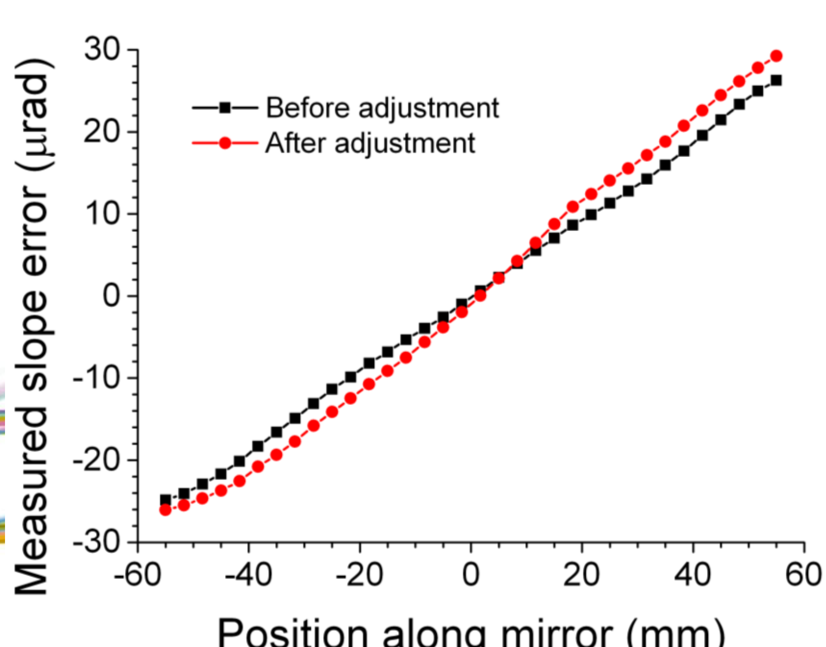
This could provide a simple rating for the quality of defocused beam.

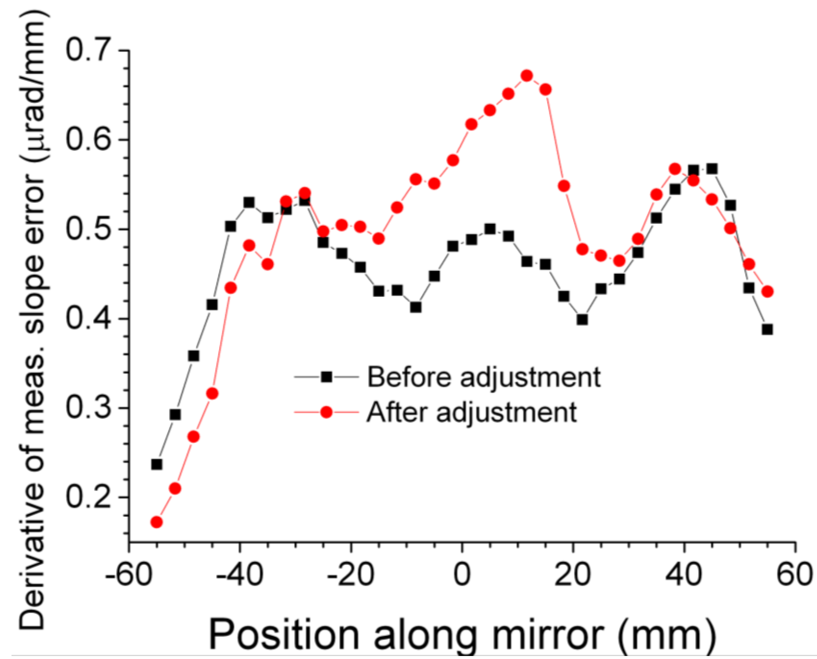
Can this insight help us reduce beam structure?

Manual procedure:

- Take in-situ pencil-beam scan.
- Numerically differentiate scan to find regions of low curvature.
- Adjust electrodes to increase curvature at those regions.

Tested using EEM bimorph at DLS beamline B16:



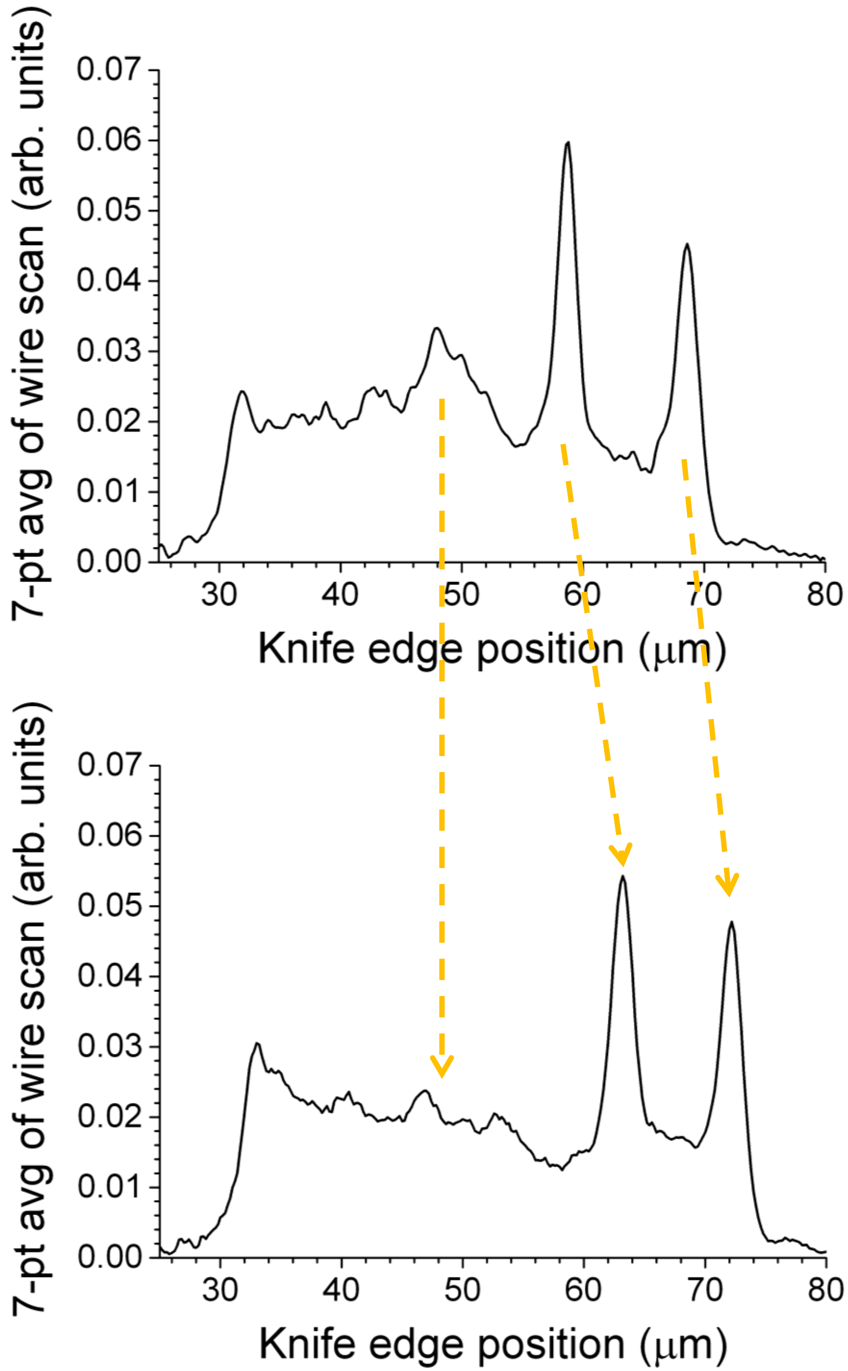


diamond

Before adjustment

After adjustment:

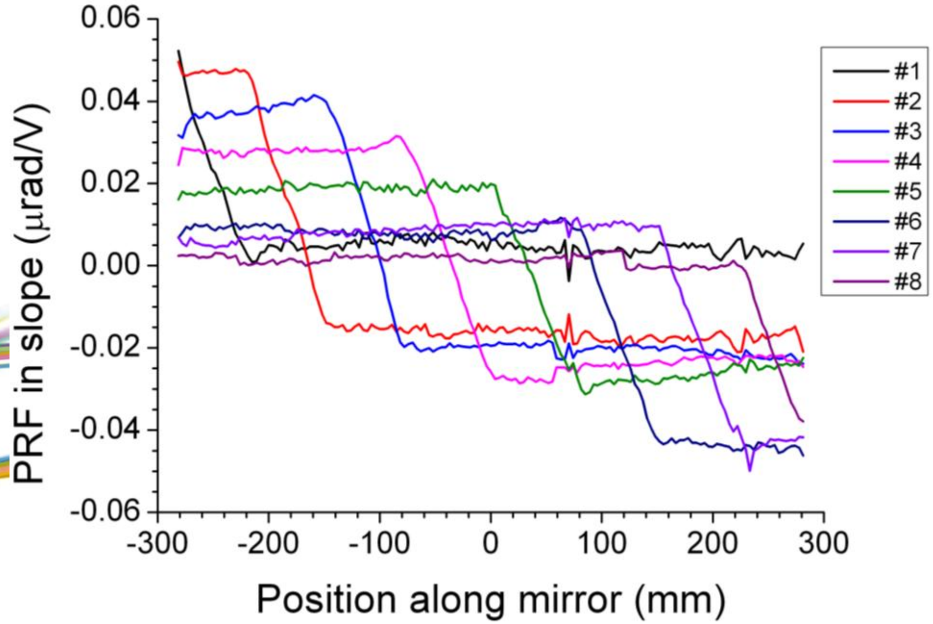
- Central hump removed
- Sharp peaks moved out



How might future bimorph mirrors be designed for smooth defocusing?

We design a computerized "model bimorph" that can help us simulate a mirror's performance.

To develop a realistic model, we go back to our original test case, the vertically focusing mirror at Diamond beamline I02:



Note: PRFs of all electrodes look very similar –
Only central position of jump changes from one to the next.
→ we can model the PRFs using a common functional form!

Model PRF for jth electrode of an N-electrode mirror of length L =

$$(A/2)*\text{erf}[\ 2(x-x_j)/fw_j\ ] + s_j\ ,$$

where

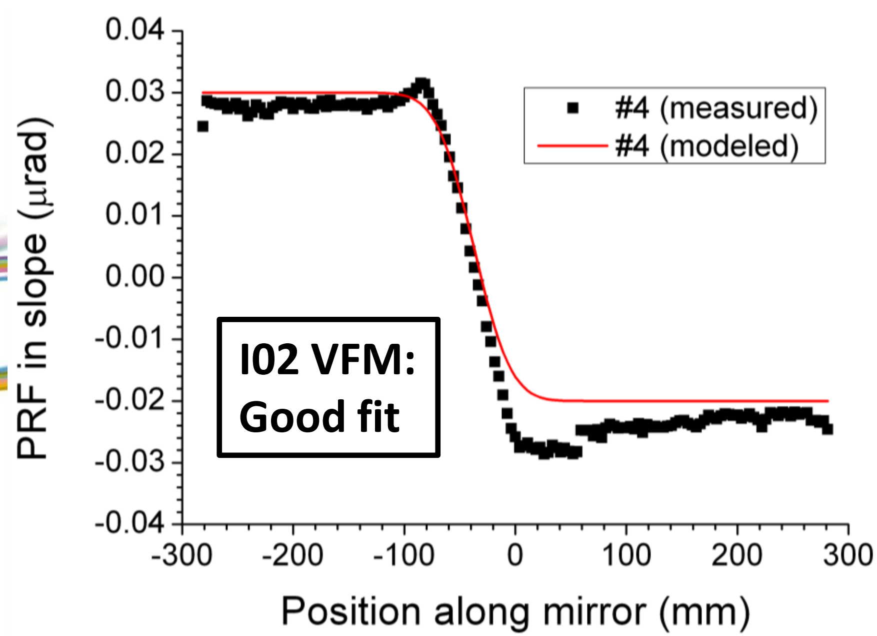
A = magnitude of jump

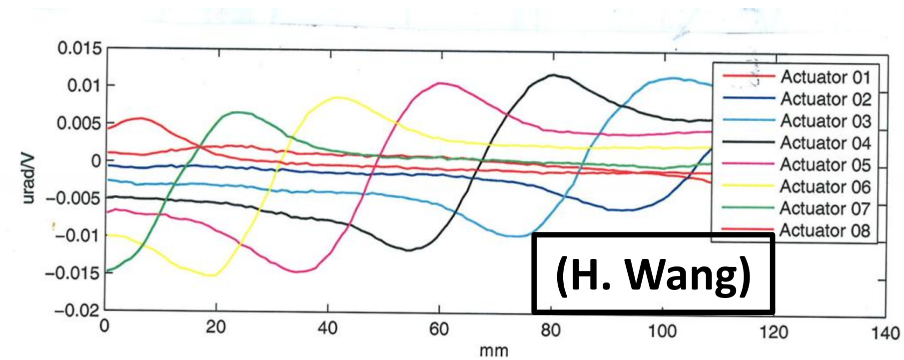
x_j = centre of electrode: assumed equally spaced

f = dimensionless fraction

w_j = electrode interval = L/N

s_j = vertical shift of PRF



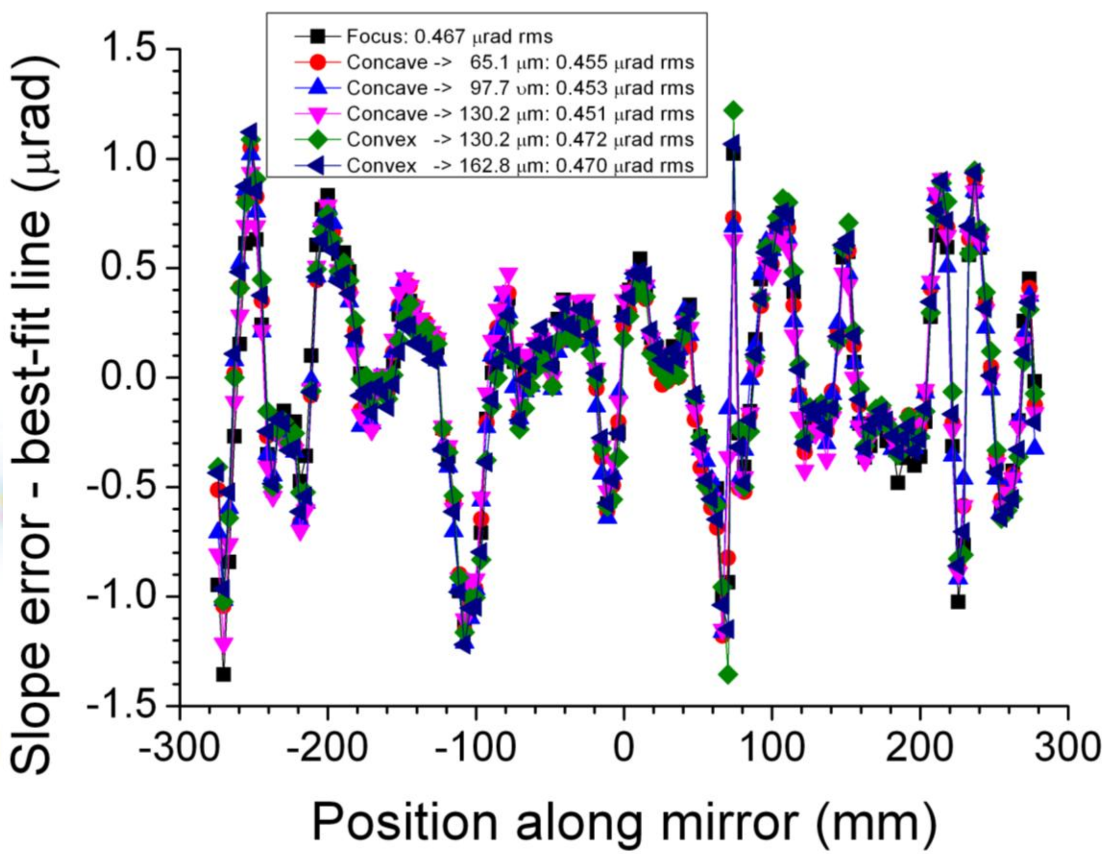


Super-polished bimorph:
Strong overshoot/undershoot not captured in model!

diamond

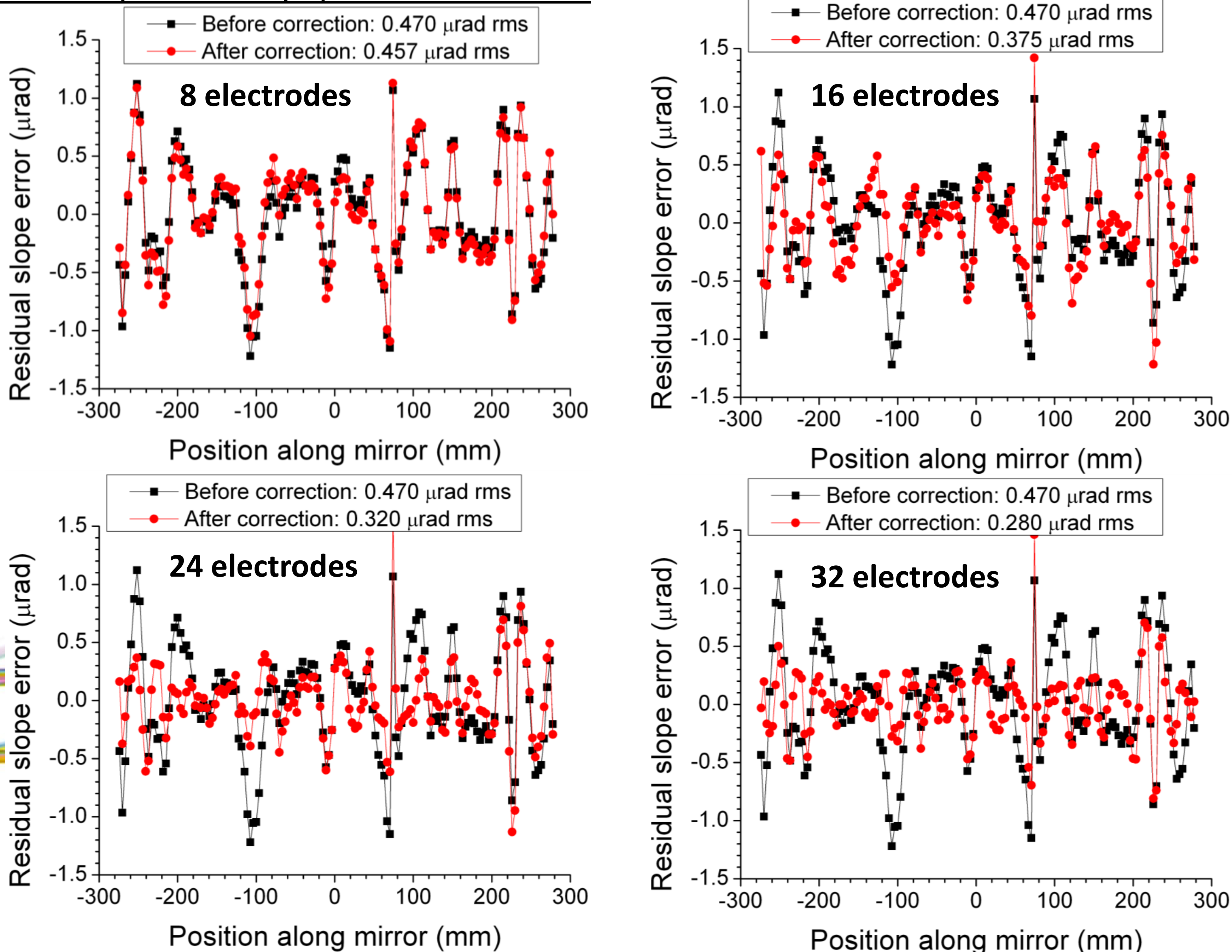
Could more electrodes improve the defocusing performance?

Measured in-situ slope error with pencil-beam scans
after applying uniform extra curvature to mirror.
→ residual slope error (slope error measured in situ – best-fit line)
is remarkably independent of beam size chosen.

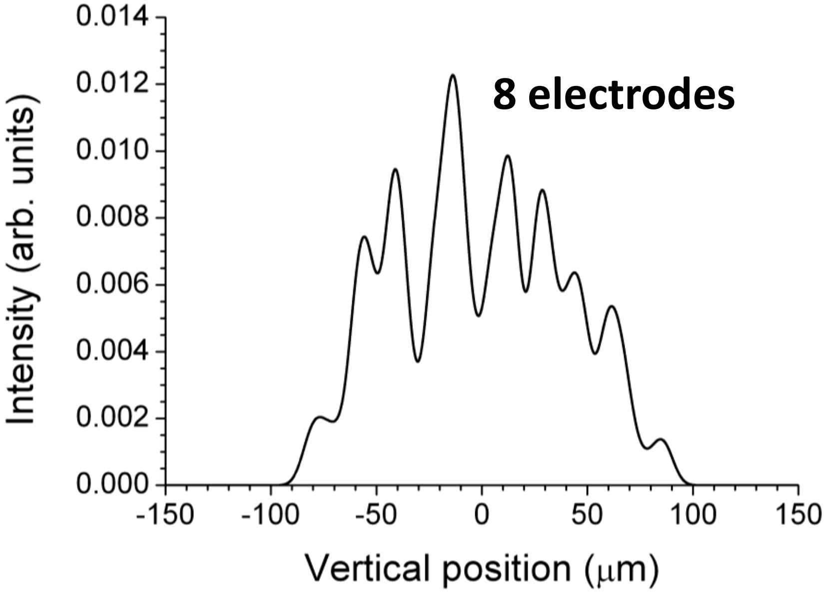


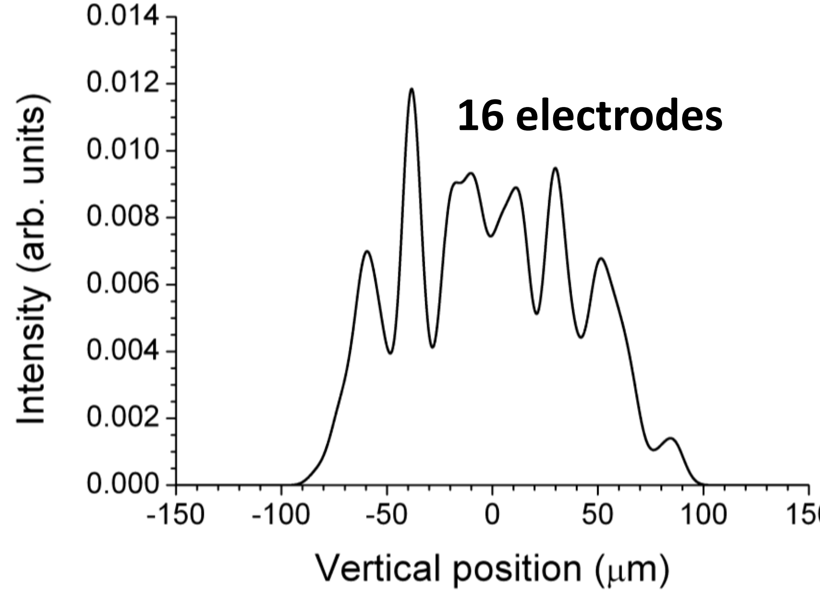
diamond

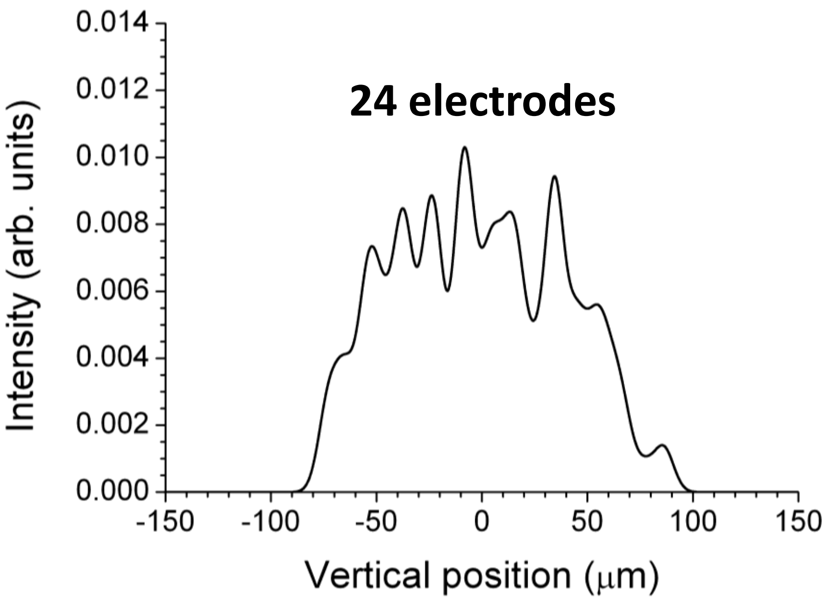
Simulate periodically spaced electrodes:

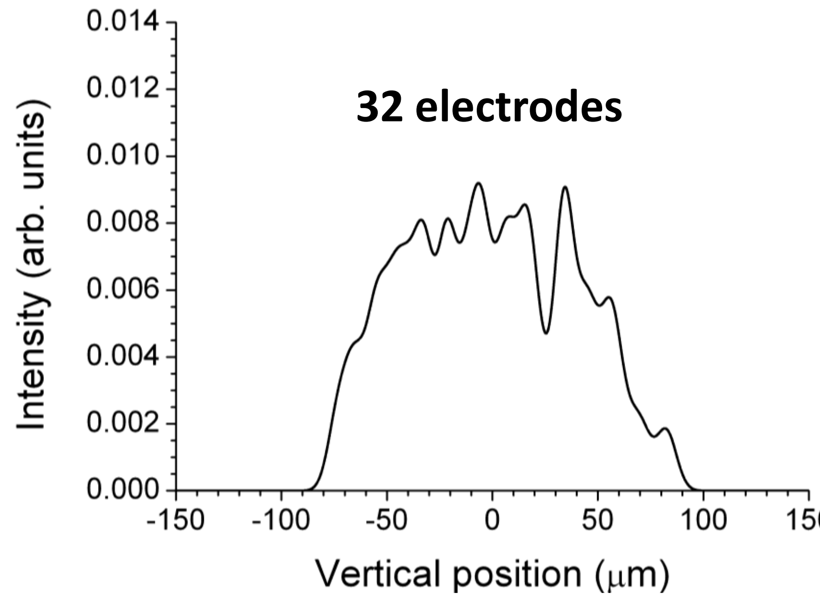


Beam profiles simulated using mirrors adjusted with model PRFs:









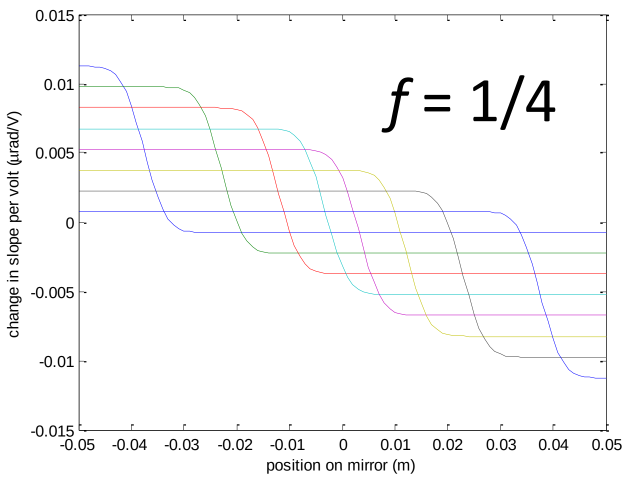
Convex additional curvature, requested beam size = 162.8 μm

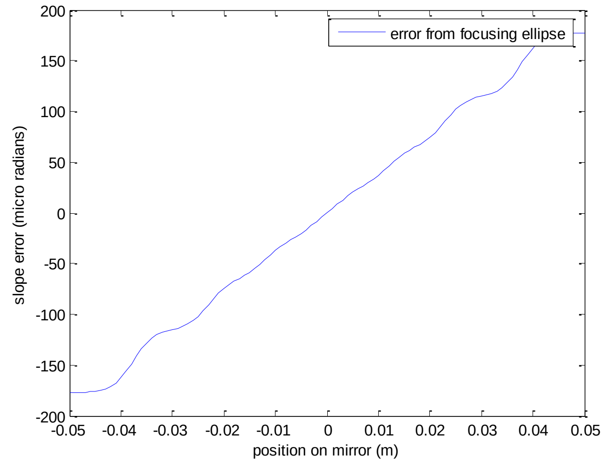
Could non-periodic electrodes improve the defocus more rapidly?

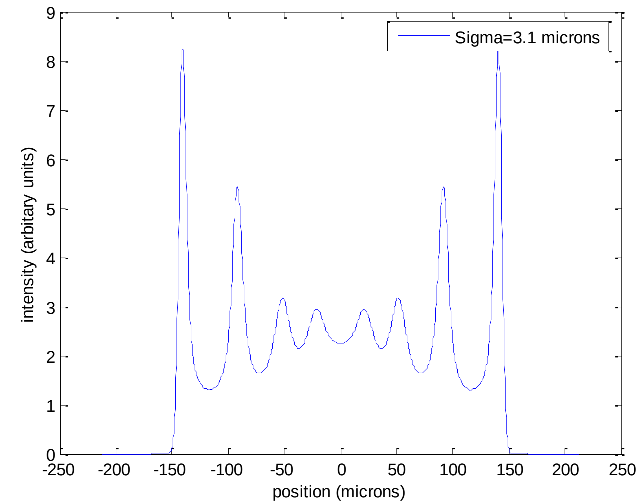
Simulate modified EEM bimorph (8 electrodes):

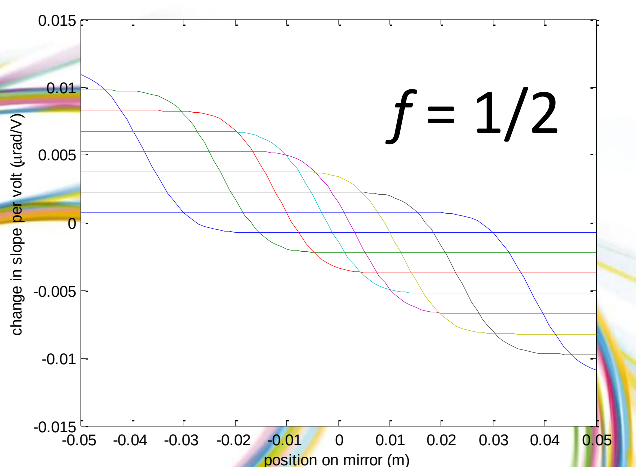
Best calculated results obtained by increasing overlap between electrodes at center:

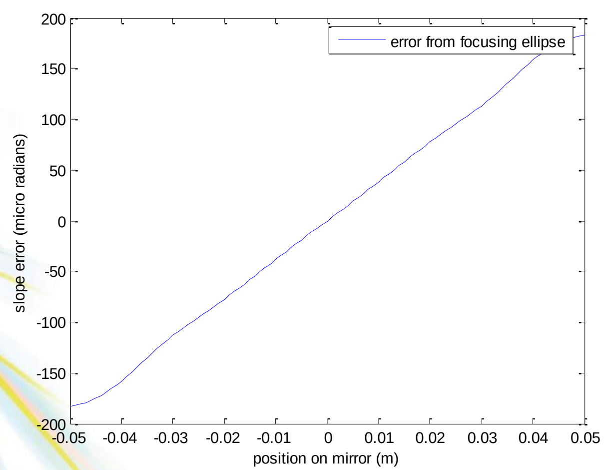
Model PRFs | Slope deviation for defocus | Calculated beam profile

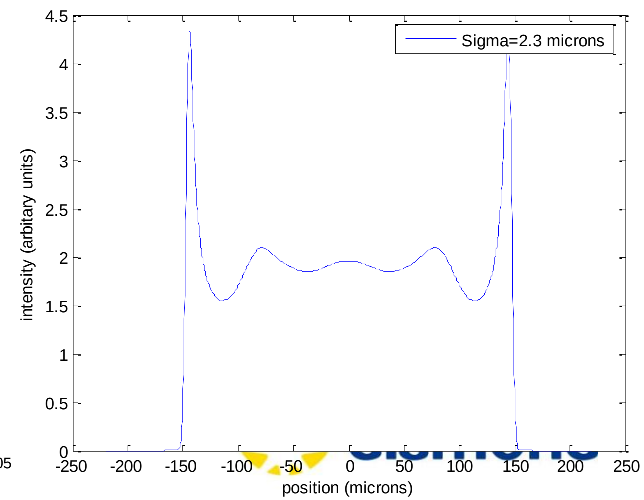












Conclusions

- Can mirror slope errors be related to defocused beam structure?

A simple, purely geometrical model can generate theoretical beam profiles from pencil-beam scans in good agreement with experiment.

- How carefully must mirror slope errors be controlled?

Structure is still visible in defocused beam even at rms slope errors of 0.15 μrad.

- How might mirror polishing errors be specified – is rms enough?

For defocused beams, local curvature error (derivative of slope error) is also important – hot spots appear when this is zero.

- How might future mirrors be designed for smooth defocusing?

Increased electrode density does reduce rms slope error and defocused beam structure, but not rapidly.
Increased electrode overlap at center, however, shows improvement.

Thanks to:

Thomas Sorensen, Juan Sanchez-Weatherby & James Sandy (I02, DLS)

Hongchang Wang (Optics & Metrology, DLS)

and of course to all of you for listening!