Measurement and analysis of active mirror slope errors under operating conditions

John P. Sutter, Simon G. Alcock & Kawal Sawhney

Diamond Light Source Ltd, Harwell Science and Innovation Campus, Chilton, Didcot, Oxfordshire OX11 0DE, United Kingdom

The quality of active optics may be measured

• ex-situ: in a special metrology laboratory

  - precise test of quality under carefully controlled conditions

• in-situ: under realistic operating conditions

Both types of measurements are performed on active mirrors at Diamond Light Source:

• ex-situ: in our in-house metrology laboratory equipped with
  - BESSY-type NOM
  - Fizeau interferometer
  - micro-roughness interferometer

• **in-situ: on the synchrotron beamlines where the mirrors are installed, using only equipment that is already installed or can be installed without breaking vacuum.**

Sometimes ex-situ and in-situ measurements support each other.

Sometimes in-situ measurements provide vital information that ex-situ measurements cannot.

Examples of both cases will be presented here.

Only well-known methods have been used to collect the data: pencil-beam scans + interaction matrix calculations.

But at Diamond Light Source, they have been applied to new problems:

- surface stability of bimorph mirrors
- discovery and remediation of surface defects
- diagnosis of malfunctioning actuators
- optimisation of a *collimating* mirror.

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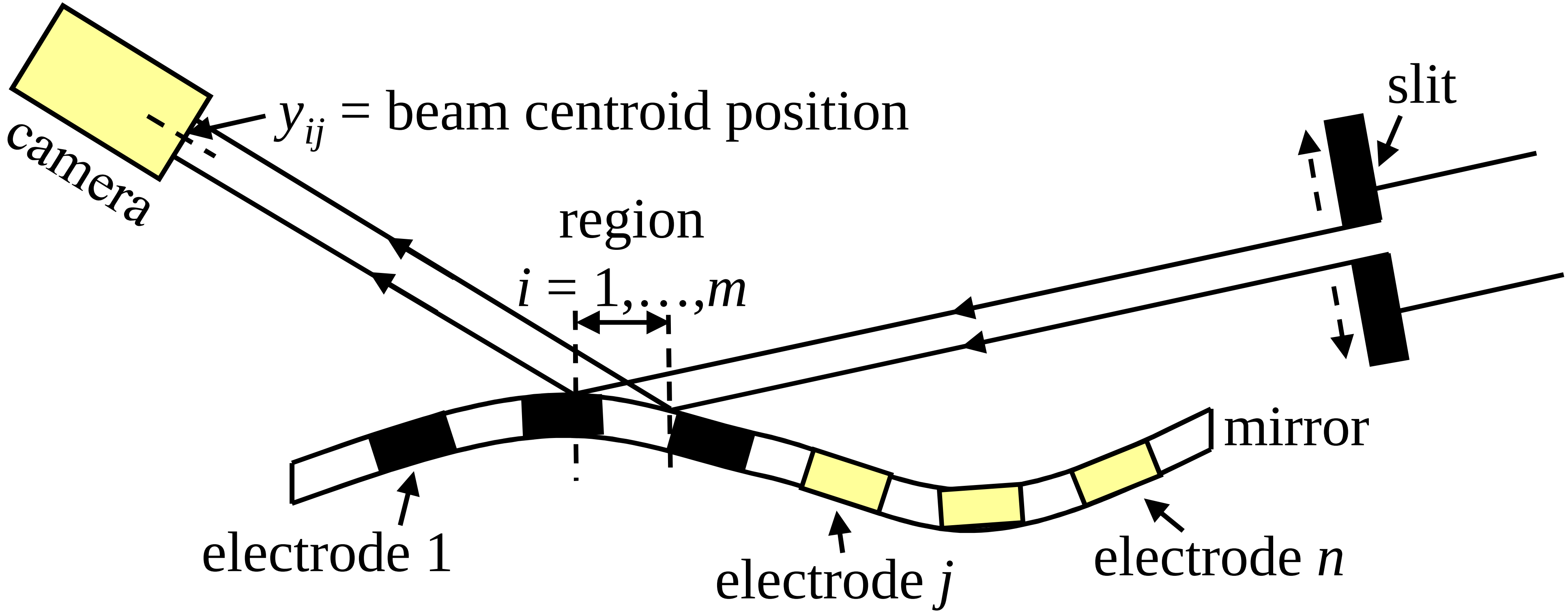
Pencil beam method as performed in-situ on bimorph mirrors:

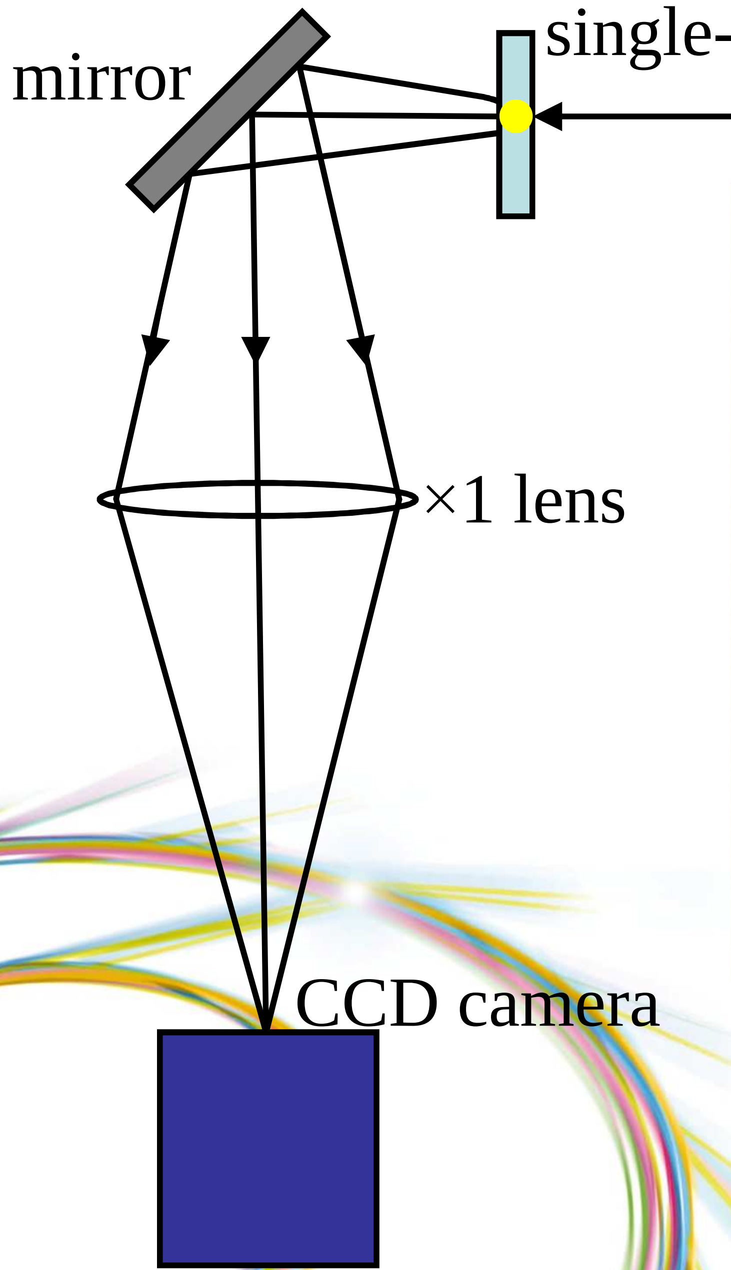


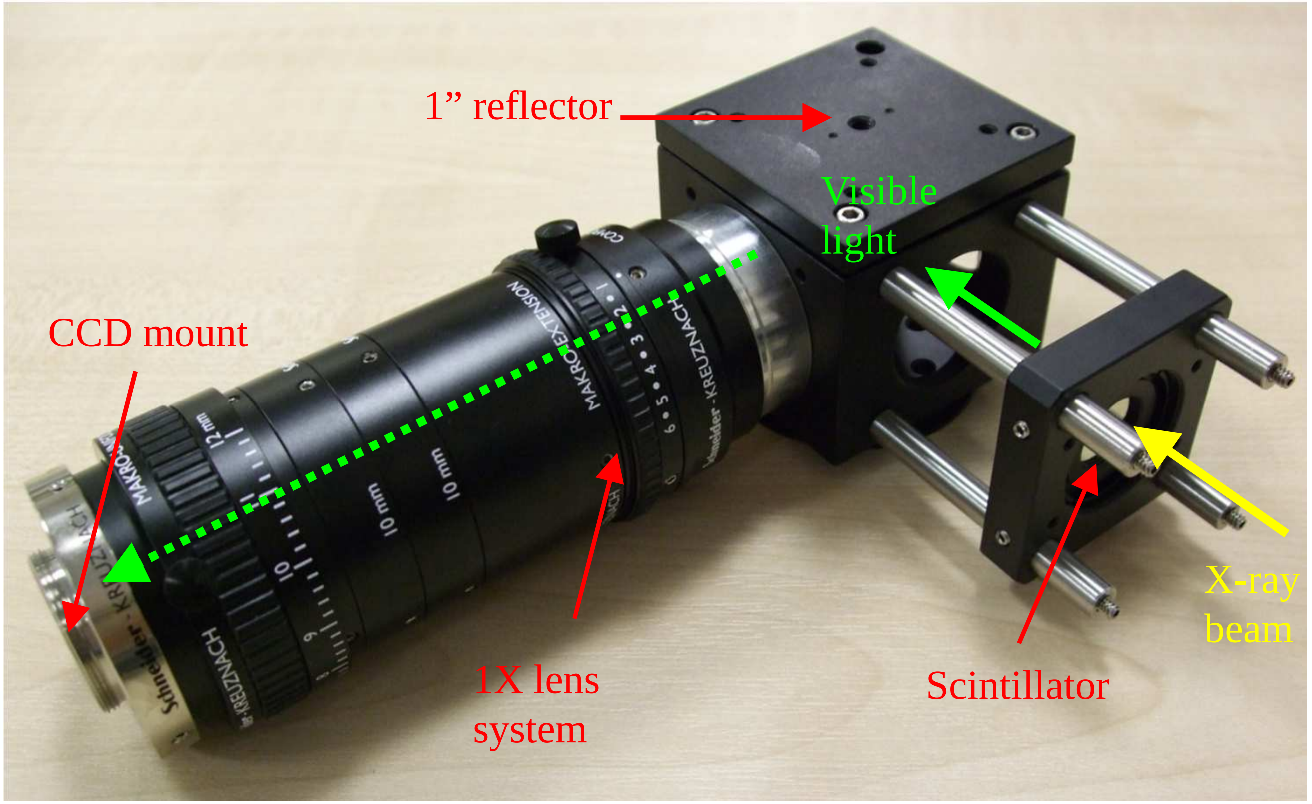
Scan a small (~10 μm) slit across incident beam.
Record beam position in camera.

The "camera" may be a real imaging device or a detector behind a scannable slit.

X-ray camera designed by our Diagnostics group:

This camera is small and portable –
used at several beamlines that lack their own imaging systems.





Camera image transmitted on Firewire/GigE.

90% integrated line spread function ~ 6.35 μm

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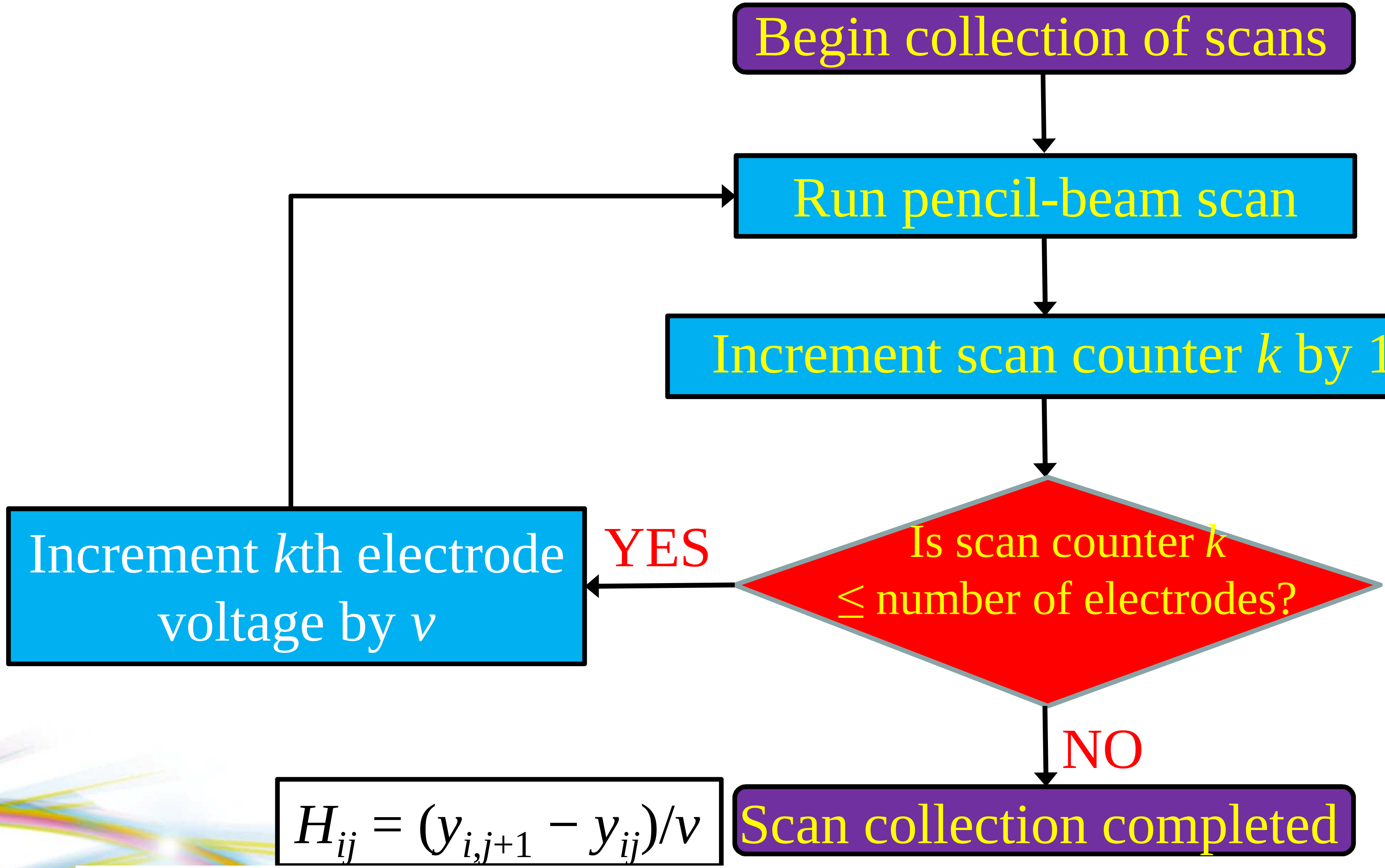
Interaction matrix H: Shows each actuator's effect on figure.



$$H_{ij} = (y_{i,j+1} - y_{ij})/v$$

Vector Y: Y_i = ith correction to reflected beam position

Vector V: V_j = voltage correction for jth electrode

Shortest length least squares solution: $V = H^{\dagger}Y$

$H^{\dagger}$ = Moore-Penrose pseudoinverse of H

An automated procedure now exists to perform the pencil beam scans and interaction matrix inversion.

Only standard software packages were used:

Motors and X-ray camera image collection were controlled through EPICS.

Pencil-beam scans were executed and analyzed using the Generic Data Acquisition (GDA) package.

Jython scripts were used to
- calculate the beam centroid position using a 2-D Gaussian fit
- calculate and invert the interaction matrix.

NOTE: the centroid calculation is reproducible to within 0.1 pixel → the line-spread function does not limit the resolution.

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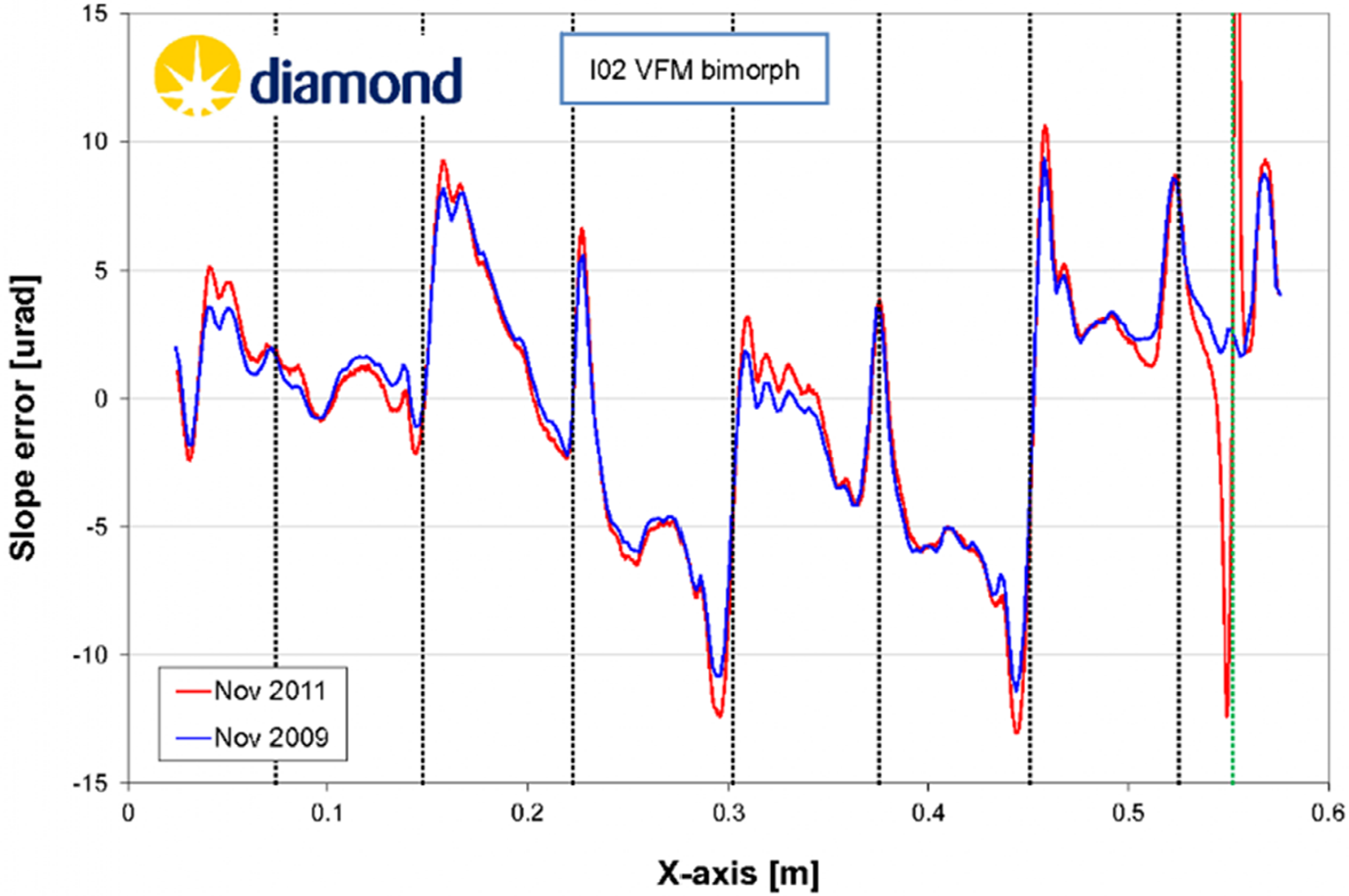
In the following, the angular resolution ~ 0.1 µrad.

J. Sutter, S. Alcock & K. Sawhney, *Proc. SPIE* **8139**, 813906 (2011)

Ex-situ measurements revealed a “junction effect” in bimorph mirrors: violent jumps in slope error at the junctions of the piezoelectric plates:

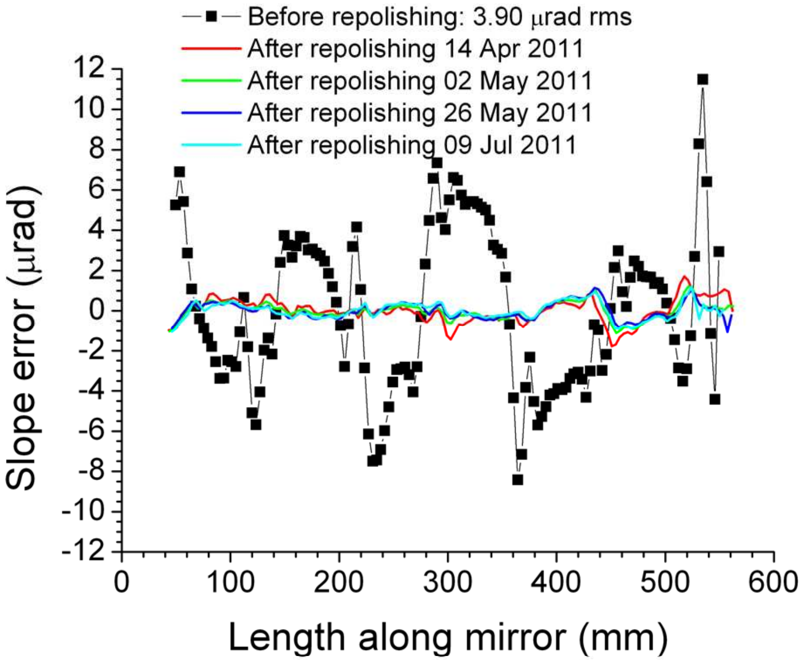


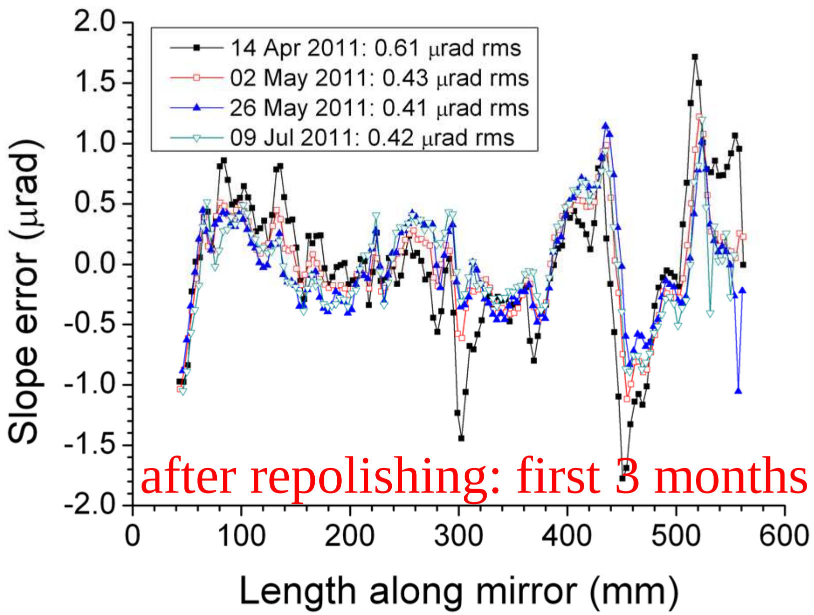
Measured on Diamond NOM

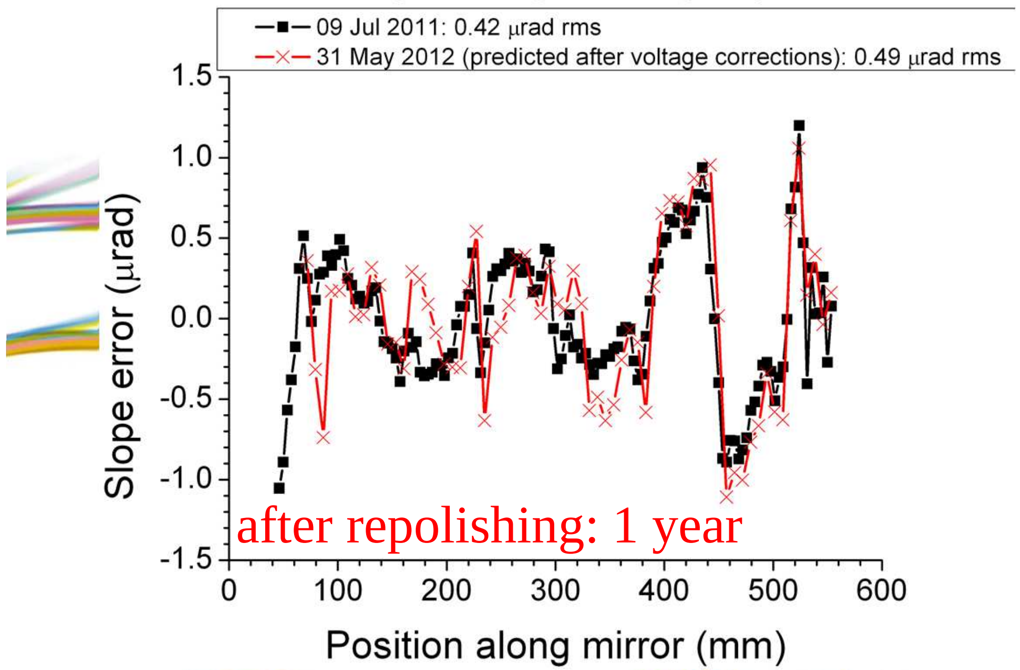
Dotted lines are junctions.

Figure stable over 2 years of operation!

In-situ measurements agree with these ex-situ results.
Corrugation was removed on two sets of KB mirrors by repolishing.
In-situ scans and new beam images confirmed success.







Vertical focusing mirror
at I04 before repolishing,
at I03 after repolishing.

Surface after repolishing was stable over 1 full year.

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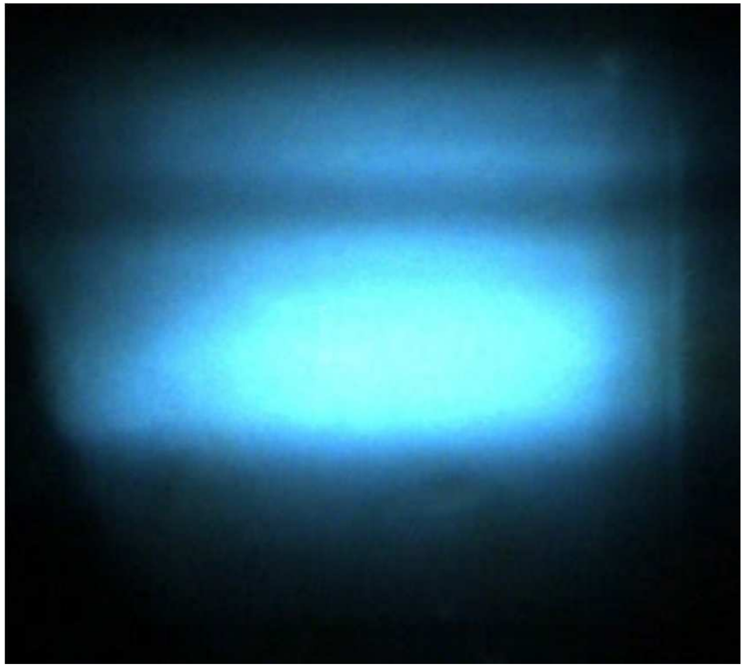
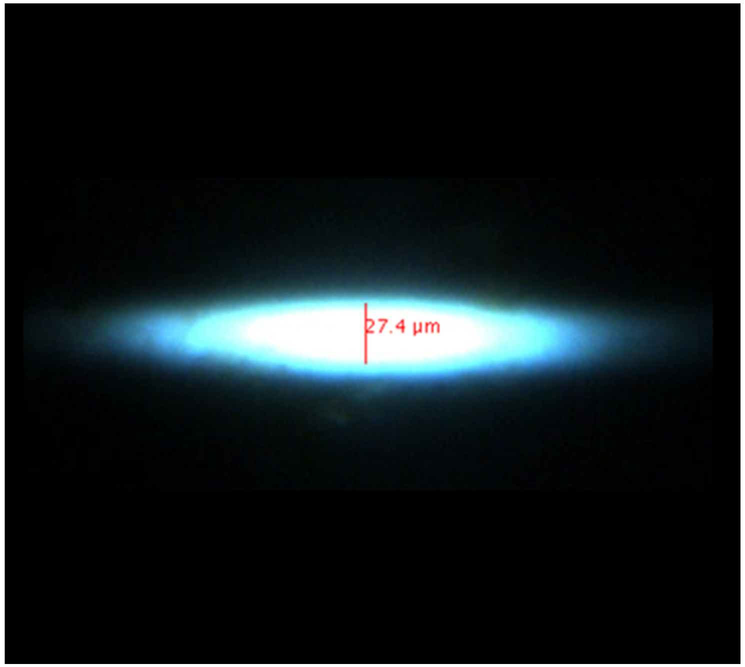
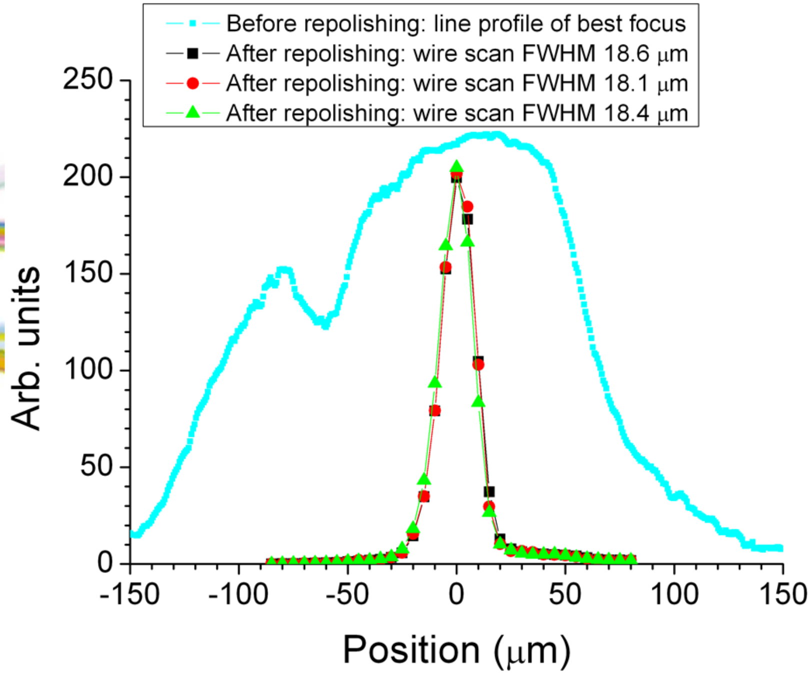


Before at I04



Immediately after re-installation of VFM at I03



Horizontal focusing mirror was likewise re-polished and re-installed.

Horizontal beam width reduced from 120 µm to 70 µm (theoretical 65 µm)

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Pencil-beam scans also help optimise mechanically bent mirrors!

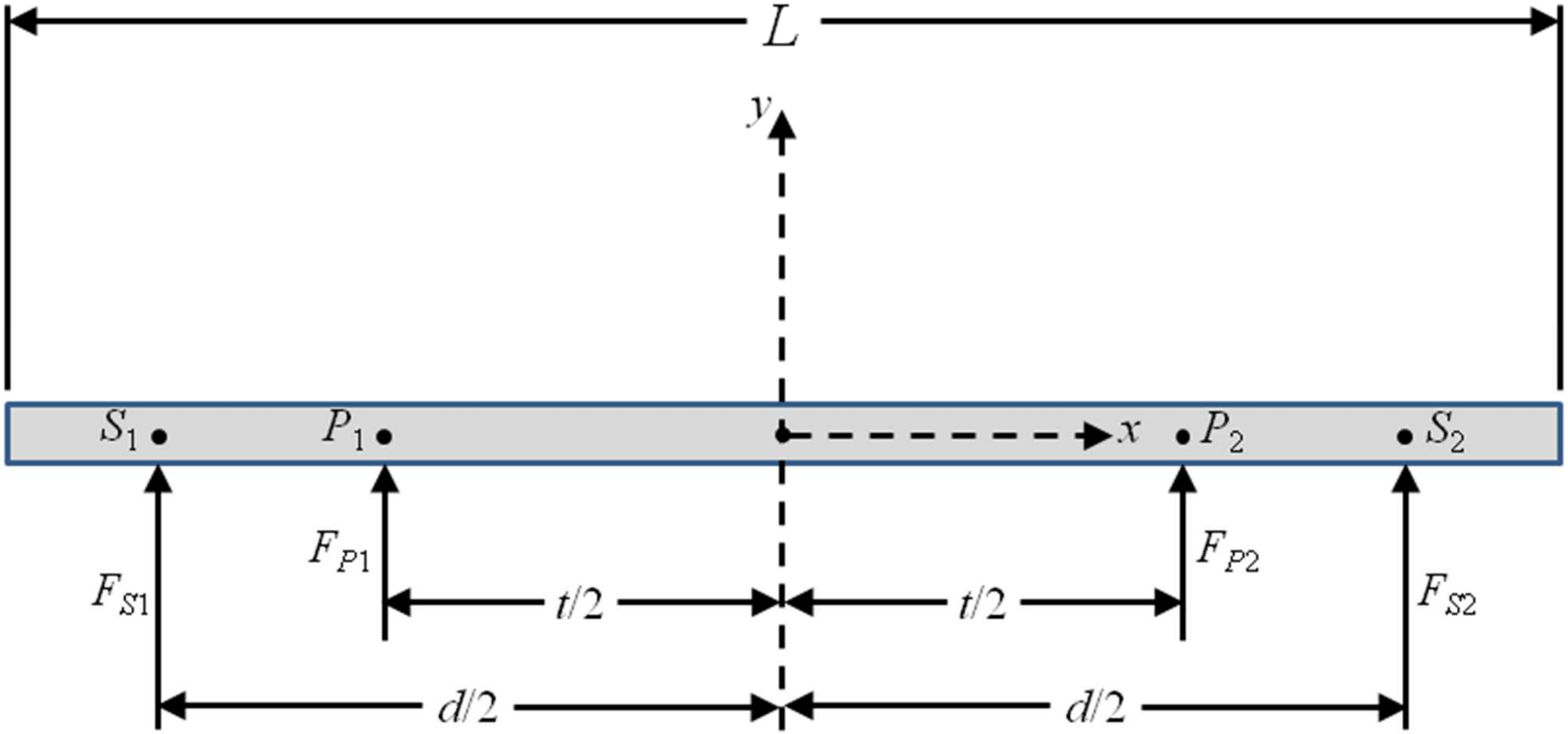
<u>Examples at Diamond Light Source:</u>
- I15 (Extreme Conditions)
- I20 (X-ray Spectroscopy)

These mirrors are flat, rectangular slabs of silicon with two bending actuators, one at each end.

The bending actuators deform the mirror into the desired shape: elliptical for focusing (I15), parabolic for collimation (I20).

But gravity adds an error-producing "sag" deformation!

To compensate, an upward force is applied by an actuator to two symmetrically positioned "props":



Standard vertically focusing mirror:
Fixed support points S_1 and S_2; prop points P_1 and P_2

Sag compensation actuator is placed in a bulky frame of preloaded springs
→ ex-situ measurements require mirror to be removed from this frame.

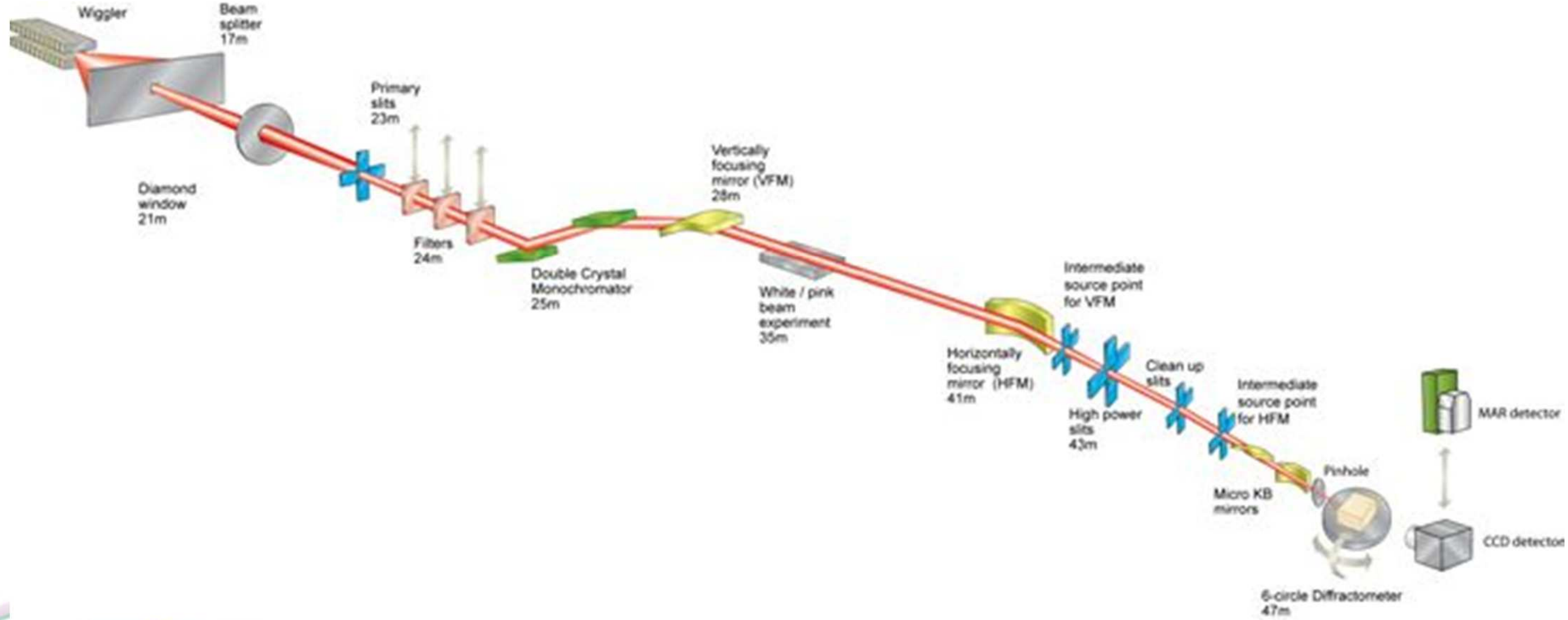
Ex-situ measurements are *not* helpful for finding the best setting of the sag compensation actuator!

In theory, finite element analysis can simulate mirror deformation versus setting of sag compensation actuator.

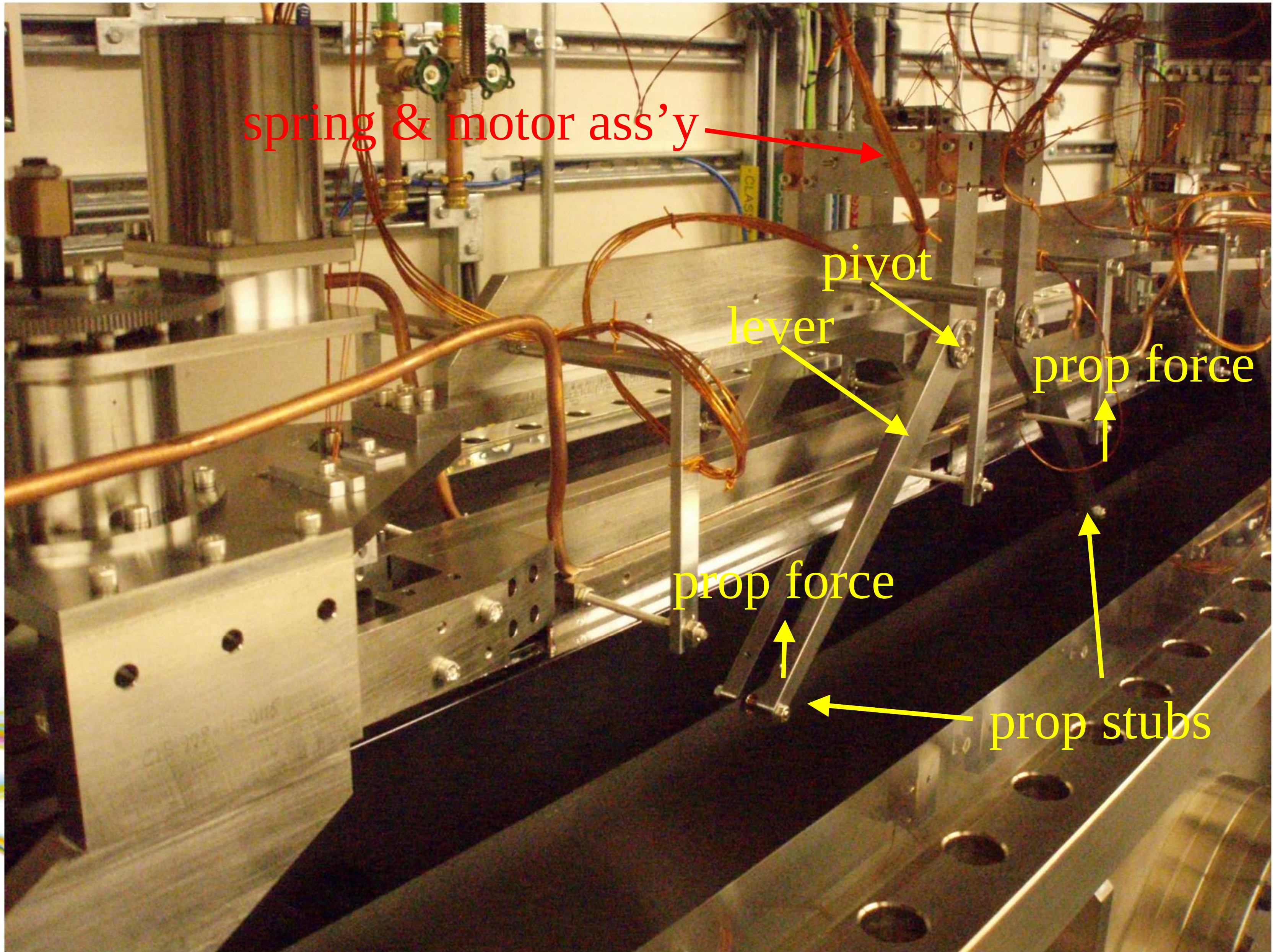
In practice,
- this calibration is often unknown or highly uncertain.
- even if measured in air, the calibration may be different in vacuum.

In-situ measurements are the only way to know that the mirror works properly.

Diamond beamline I15: Extreme Conditions

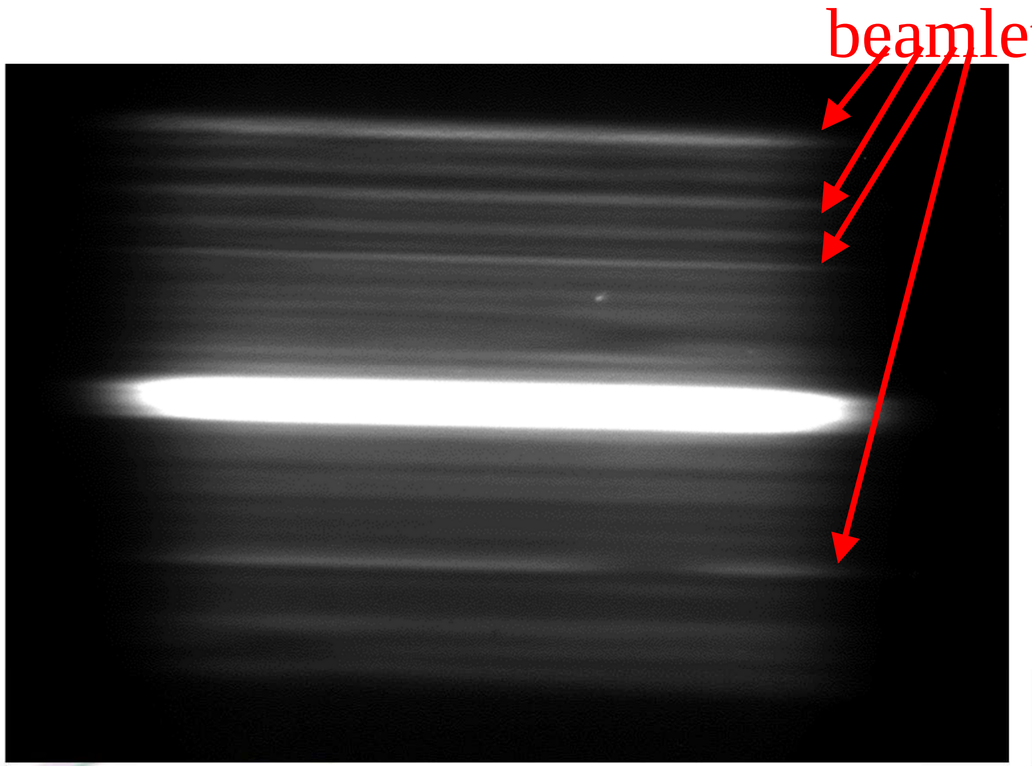


I15 Vertical Focusing Mirror



In-situ optimisation of Extreme Conditions vertical focusing mirror

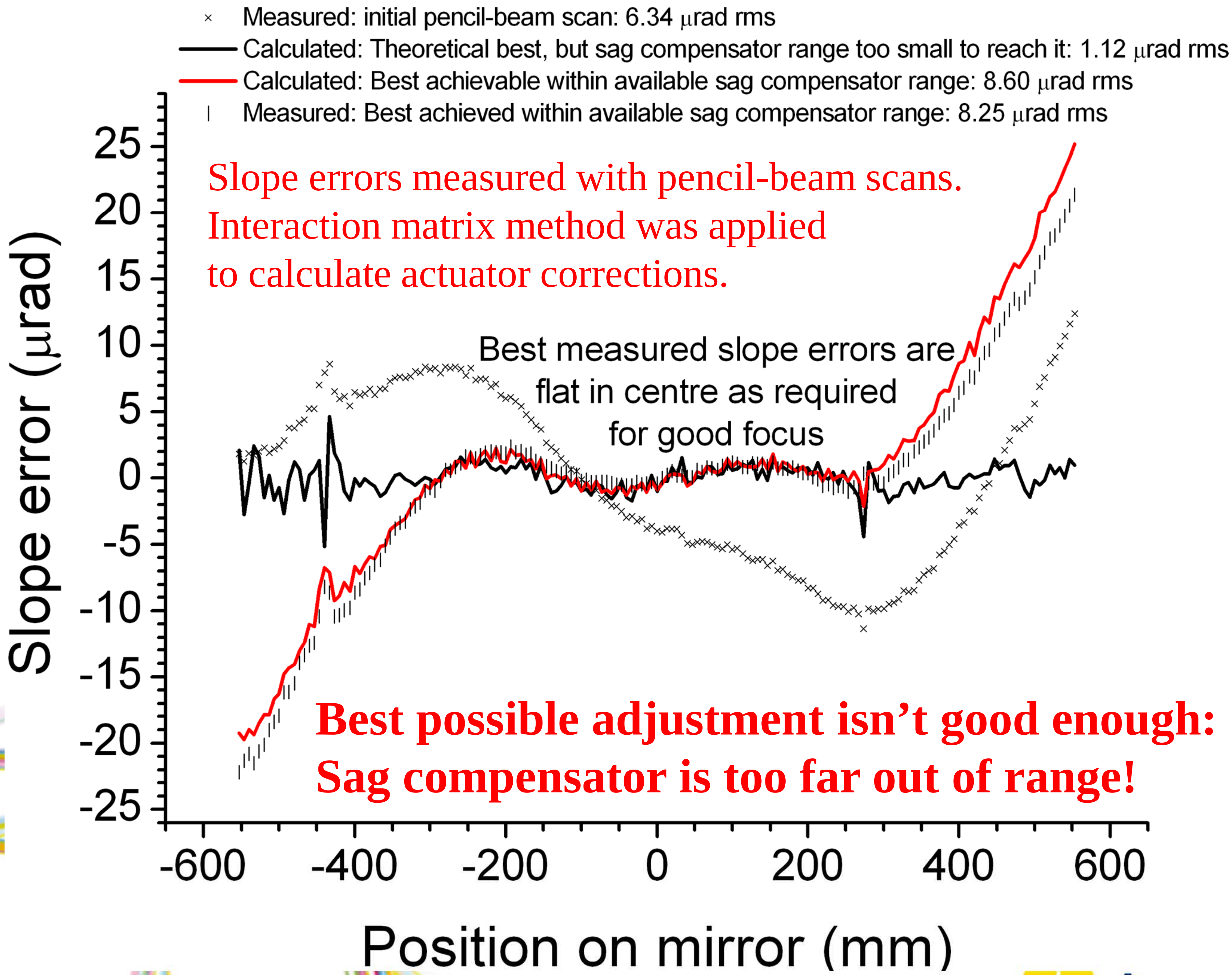
Initial focusing performance was poor.
Only the central section produced well-focused beam.



Focus: whole mirror is illuminated

Focus: only central section is illuminated

Response functions of two bending actuators and the one sag actuator were measured using pencil-beam scans.



× Measured: initial pencil-beam scan: 6.34 μrad rms
Calculated: Theoretical best, but sag compensator range too small to reach it: 1.12 μrad rms
Calculated: Best achievable within available sag compensator range: 8.60 μrad rms
| Measured: Best achieved within available sag compensator range: 8.25 μrad rms
Slope errors measured with pencil-beam scans.
Interaction matrix method was applied
to calculate actuator corrections.
Best measured slope errors are
flat in centre as required
for good focus
Best possible adjustment isn't good enough:
Sag compensator is too far out of range!
Slope error (μrad)
25
20
15
10
5
0
-5
-10
-15
-20
-25
-600
-400
-200
0
200
400
600
Position on mirror (mm)

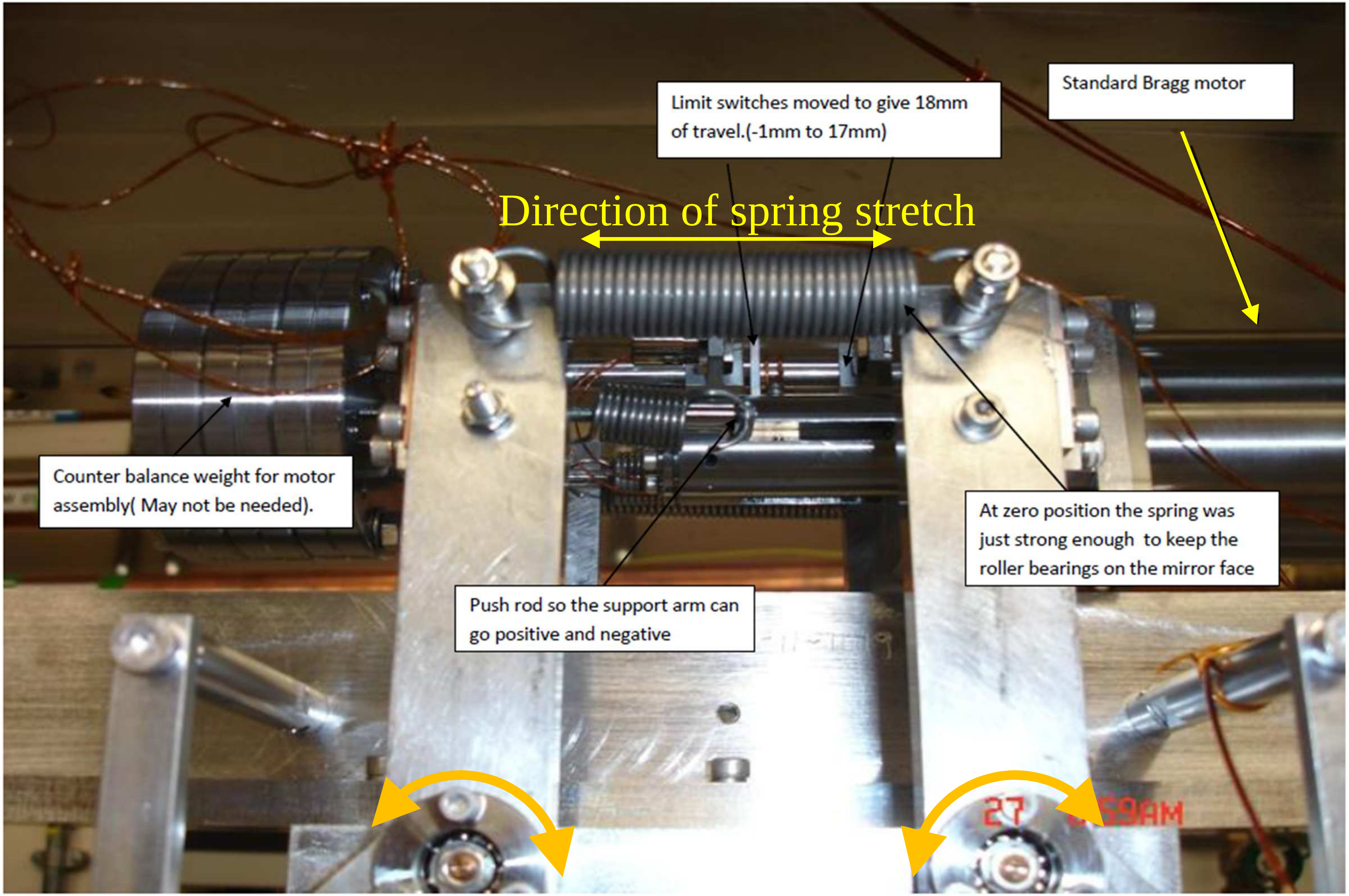
Without increasing the sag compensator's range, simulation showed no way to reduce the slope error on the edges by using the benders alone!

→ Preload had to be changed.
Softer preloading springs were placed in the compensator.

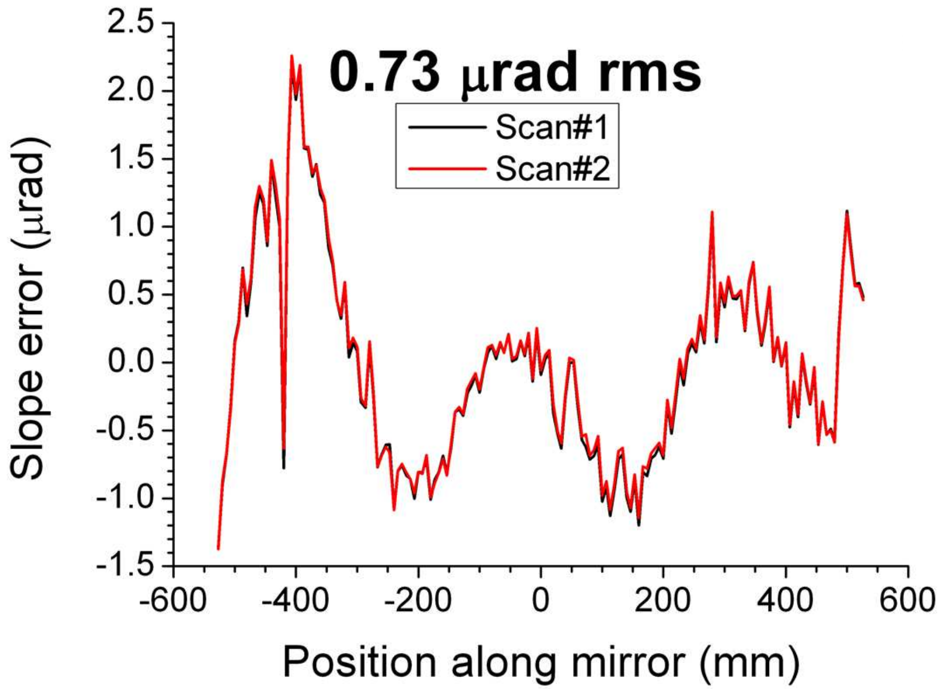
→ Compensator range had to be increased.
A stiffer spring was placed on the sag compensation motor.

Result: **dramatic improvement!**

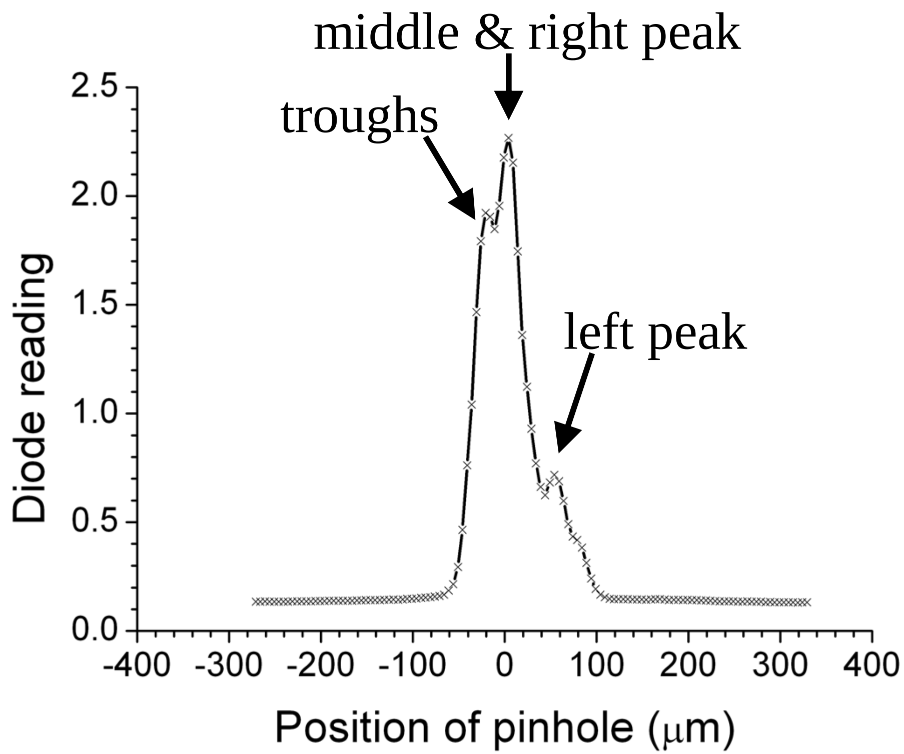
I15 VFM – New Motor and Spring Assembly



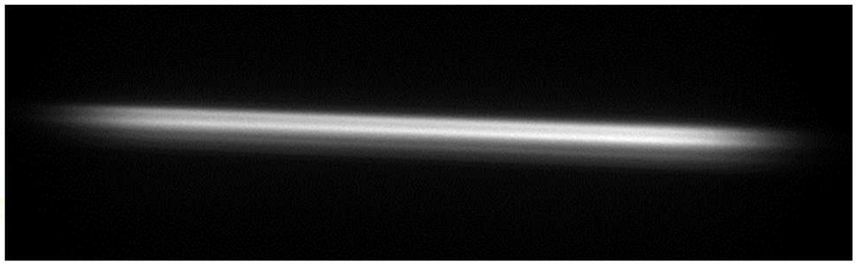
After adjustments to sag compensator springs,



Measured slope error



Vertical beam profile scan with 20 µm pinhole



X-ray camera image of focused beam

Entire mirror is now illuminated.

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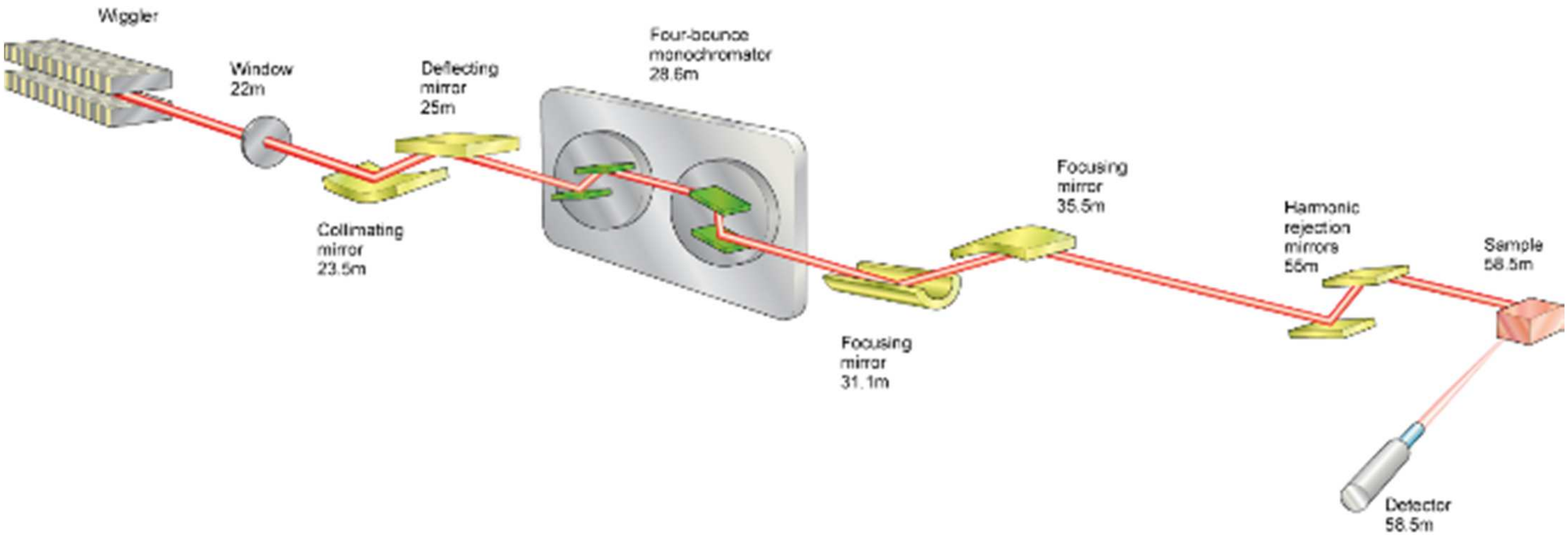
Diamond beamline I20: X-ray Absorption Spectroscopy



In-situ optimisation of I20 vertical collimating mirror

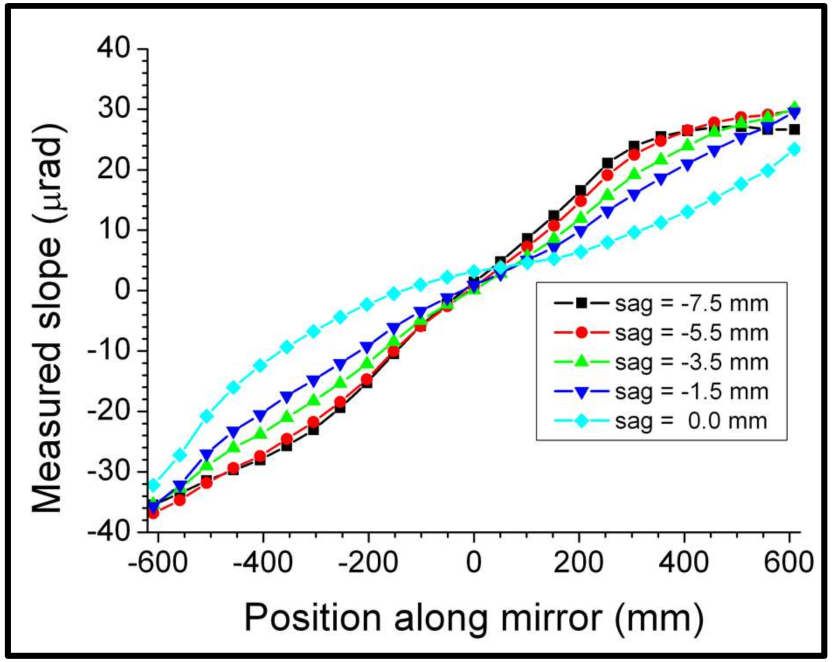
The theoretical function used to fit the measured mirror slope = $S(x) = \tau + B(x) + G(x)$:

$S(x)$ is based on the Euler-Bernoulli model of beam bending.

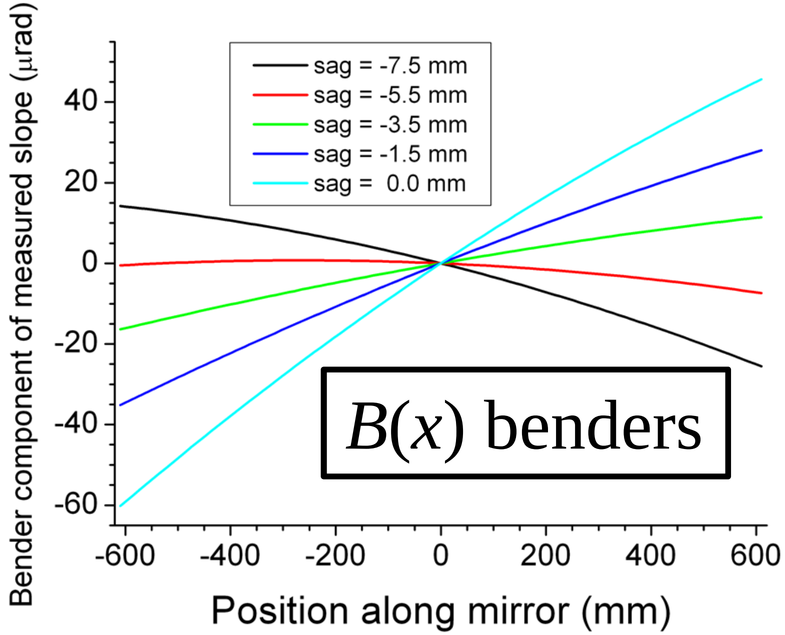
x = position along mirror: $-L/2 \le x \le +L/2$ (see L below)
τ = small uniform tilt, used as extra parameter
(Note: good fits obtained with τ from 0.59-3.14 μrad)
$B(x)$ = contribution to slope caused by benders (**quadratic**)
$G(x)$ = contribution to slope caused by gravitational sag.

Properties of mirror:
L = length of mirror = 1390 mm
Y = Young's modulus of mirror material = 1.8×10^{11} N/m^2
I = moment of inertia (ignoring cooling channel grooves)
$\approx 1.26 \times 10^{-6}$ m^4
W = weight of mirror $\approx$ 133.31 N

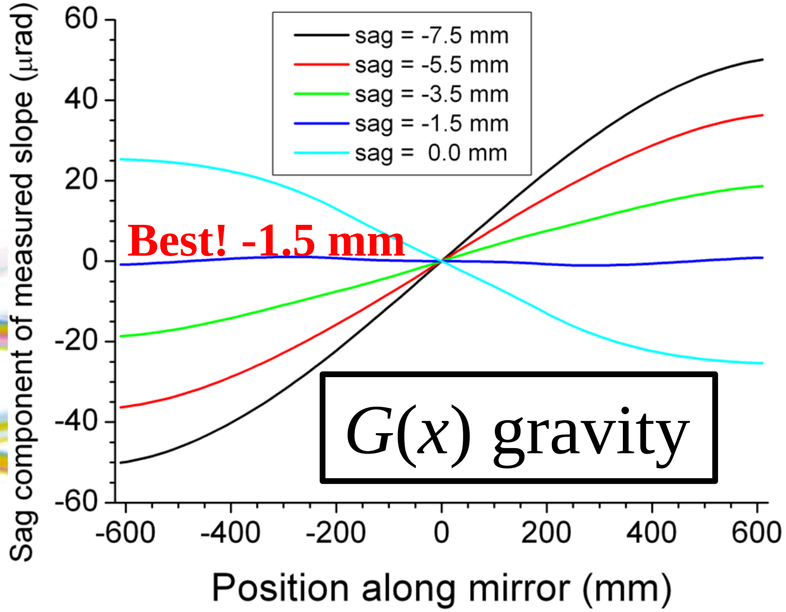
Fits of measured slope to $S(x)$:



$= \tau +$



$+$



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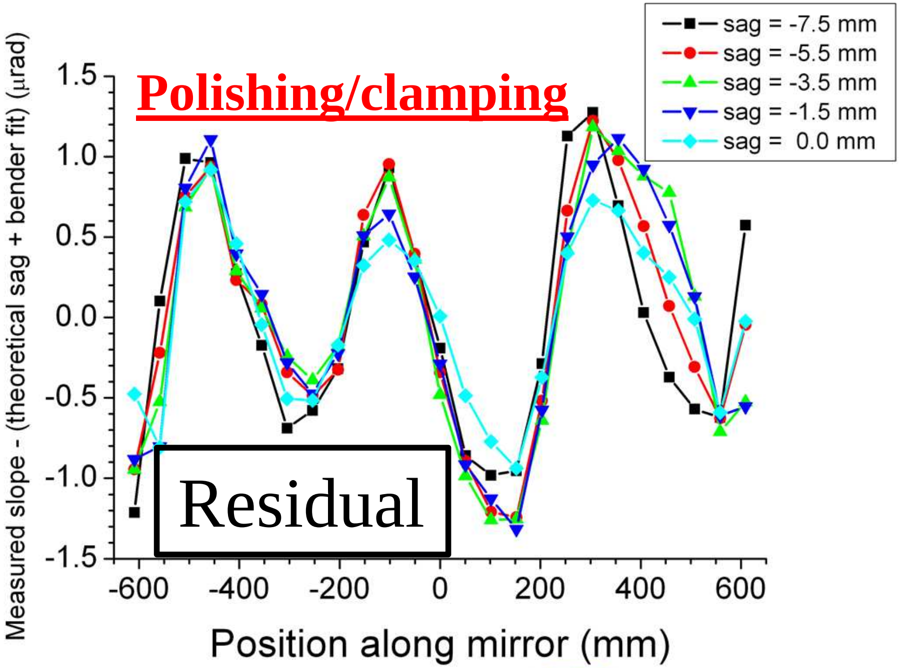

Conclusions

- In-situ pencil-beam scans can provide
  - quick and accurate test of mirror figure
  - diagnosis of malfunctioning actuators
  - correct actuator settings of focusing *and collimating* mirrors

without complex equipment or major disruption to beamline.

- The optimal sag compensation of the mechanical mirrors could not have been determined ex-situ.

- Bending actuators of mechanical mirrors cannot alone compensate the sag – <u>optimal sag compensation must be found first</u>.

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I15
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I20
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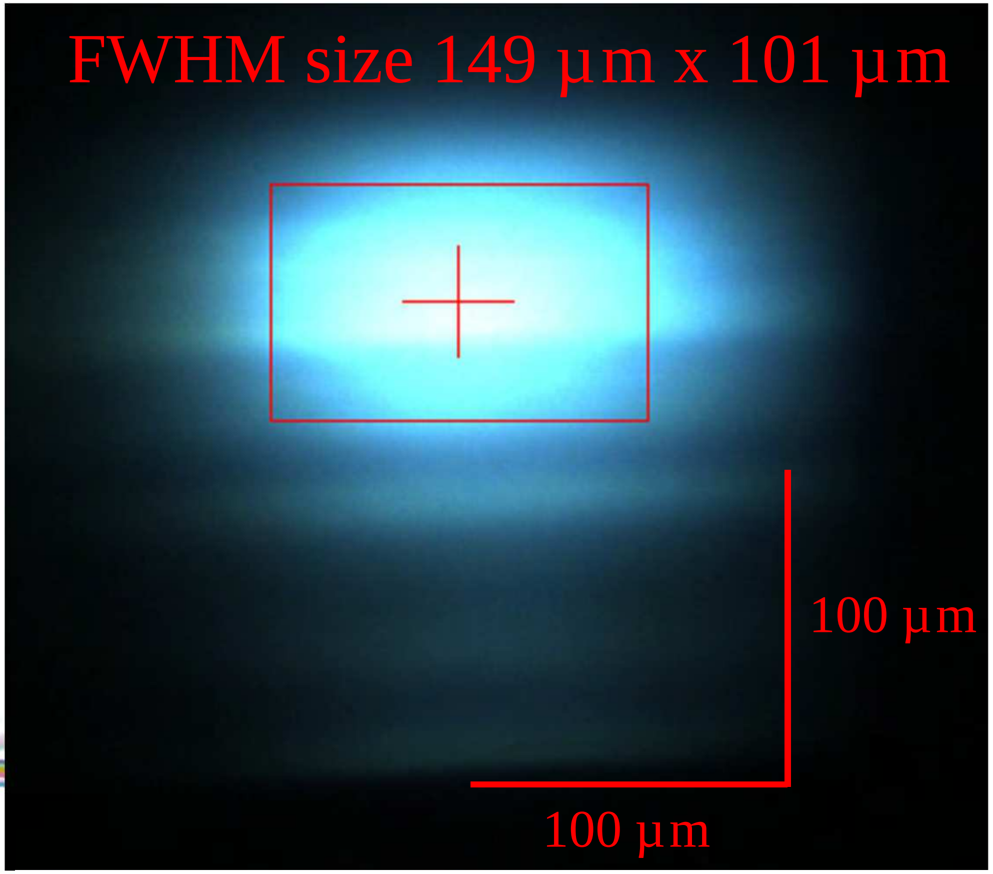
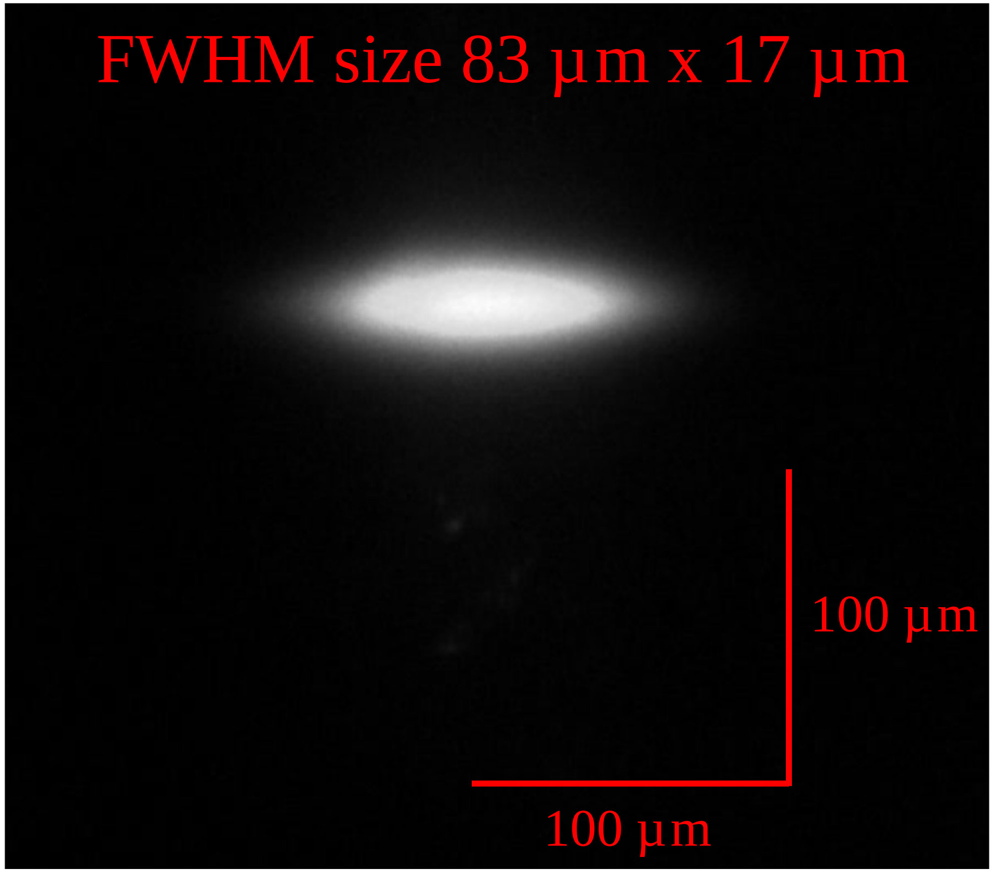
Second set of KB bimorph mirrors was taken from I03, repolished and re-installed at I02.

Commissioning late February – early March 2012:



Oct 2011: just before repolishing



Mar 2012: just after repolishing & optimisation with pencil-beam scans

Present focal size near theoretical limit!

Absolute slope error minimisation:

Sag compensation must be correctly set for good results!

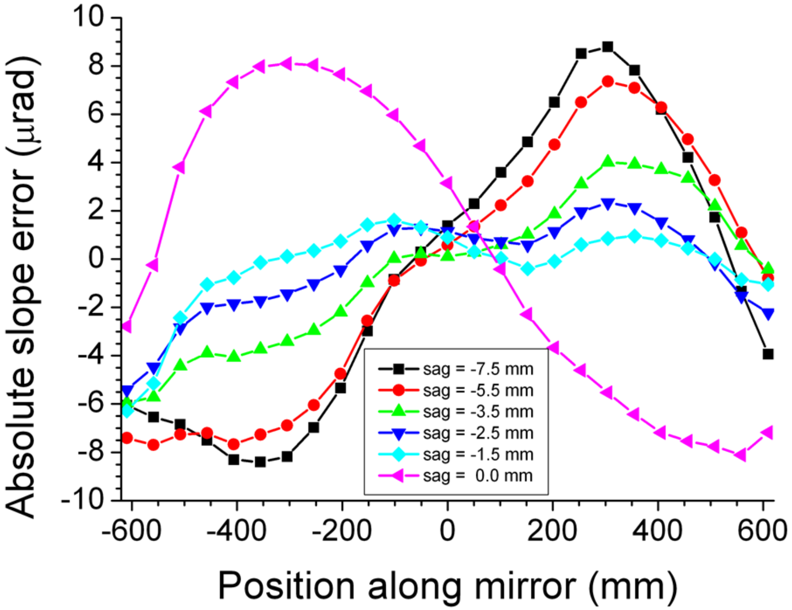
p = 23355 mm = source-mirror distance

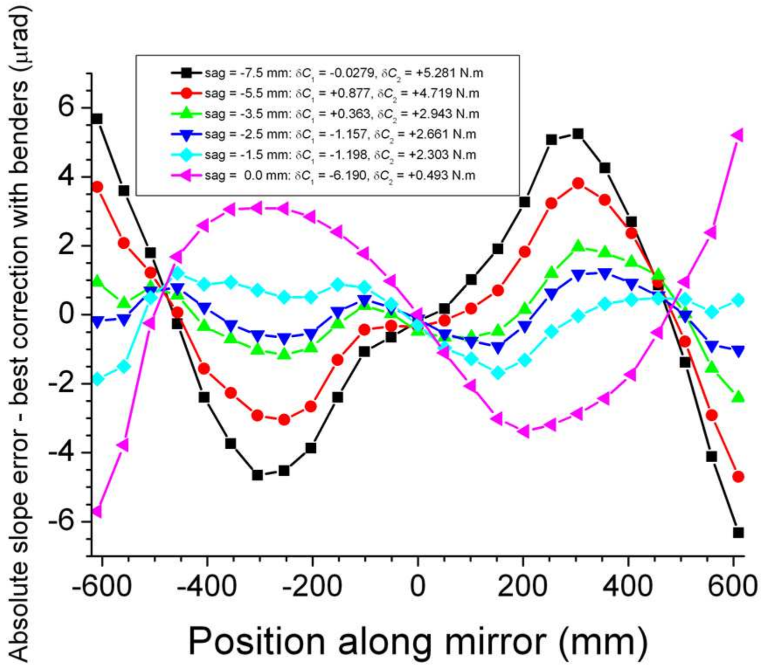
θ = 2.3 mrad = angle of incidence

→ The ideal slope profile is

$$S_{ideal} = \{ [p^{½} - (p - x \cos \theta)^{½}]/[p - x \cos \theta]^{½} \} \tan \theta$$

Absolute slope error = measured slope S_{meas} − ideal slope S_{ideal}





sag = -2.5 permits best approximation to ideal slope when benders are used!

Subtraction of best-fit quadratic from absolute slope error = best possible correction with benders at each sag

Thus, given a single pencil-beam scan of a mirror, we can estimate

- sag under gravity from $G(x)$
- required corrections to bending forces from $B(x)$.

Polishing and clamping errors were not included in this model.

To an extent they can be corrected using the actuators.

But the residuals of the fits show the polishing and clamping errors that the actuators *cannot* correct.