Fast shaping control of X-ray beams using a closed-loop adaptive bimorph deformable mirror

Simon G. Alcock[1], Ioana-Theodora Nistea[1], Vivek G. Badami[2], Riccardo Signorato[3], Matteo Fusco[4], Lingfei Hu[1], Hongchang Wang[1], Kawal Sawhney[1]

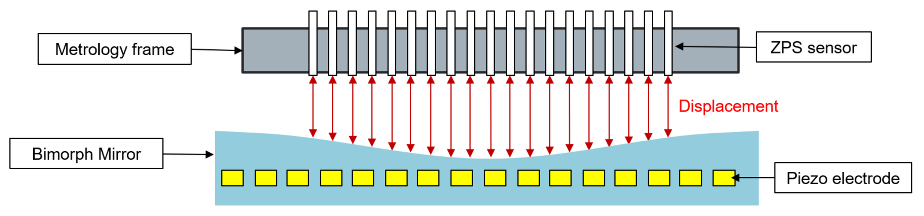
[1]Diamond Light Source Ltd, Harwell Science & Innovation Campus, Oxfordshire, OX11 0DE, UK.

[2]Zygo Corporation, Middlefield, Connecticut 06455, USA. [3]S.RI. Tech, Vigonza, Italy. [4]CAEN, Viareggio, Italy

Motivation

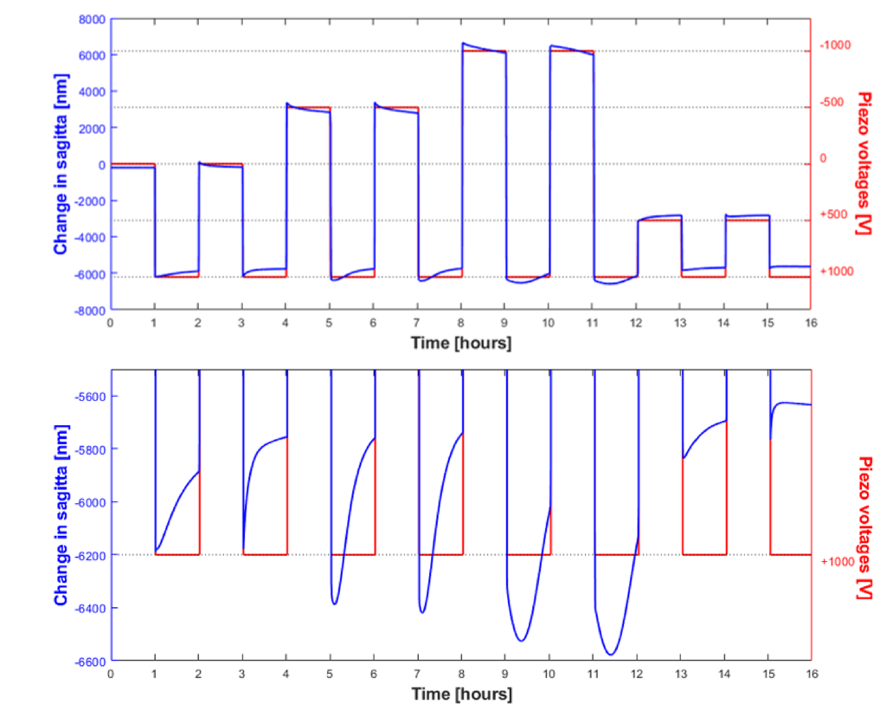
Active & adaptive X-ray mirrors

- Active X-ray mirrors for synchrotron & XFEL beamlines driven quasi-statically in open-loop. Changes every few hours or days
- Extensive R&D project at Diamond to improve beamline performance of bimorph deformable piezoelectric mirrors [1]
- High-speed adaptive mirrors, based on real-time, closed-loop feedback, benefit numerous scientific communities
- Major technological challenge for adaptive hard X-ray mirrors since surface must be controlled to single-digit nm levels



[1] J.P. Sutter et al, "Active and Adaptive X-Ray Optics at Diamond Light Source", Synch. Rad. News 35, 2 (2022) https://doi.org/10.1080/08940886.2022.2058856

Sagitta of a bimorph mirror in open-loop, as measured by ZPS sensors (blue curve), drifts unpredictably after series of large voltage steps (red curve).applied to piezo electrodes to change curvature



Why the need for fast, adaptive X-ray optics?!?

- Many beamlines want rapid changes in size or shape of X-ray beam to suit sample, whilst retaining photon-efficiency
- In extreme cases, MX beamlines scan 1000's of samples per day!
- However, curvature of bimorph mirrors drifts after large, frequent, voltage changes (upper chart) → deterioration of focal quality of X-ray beam
- Lower chart shows mirror's sagitta drifts variably by 100's of nm on each return to +1000V state

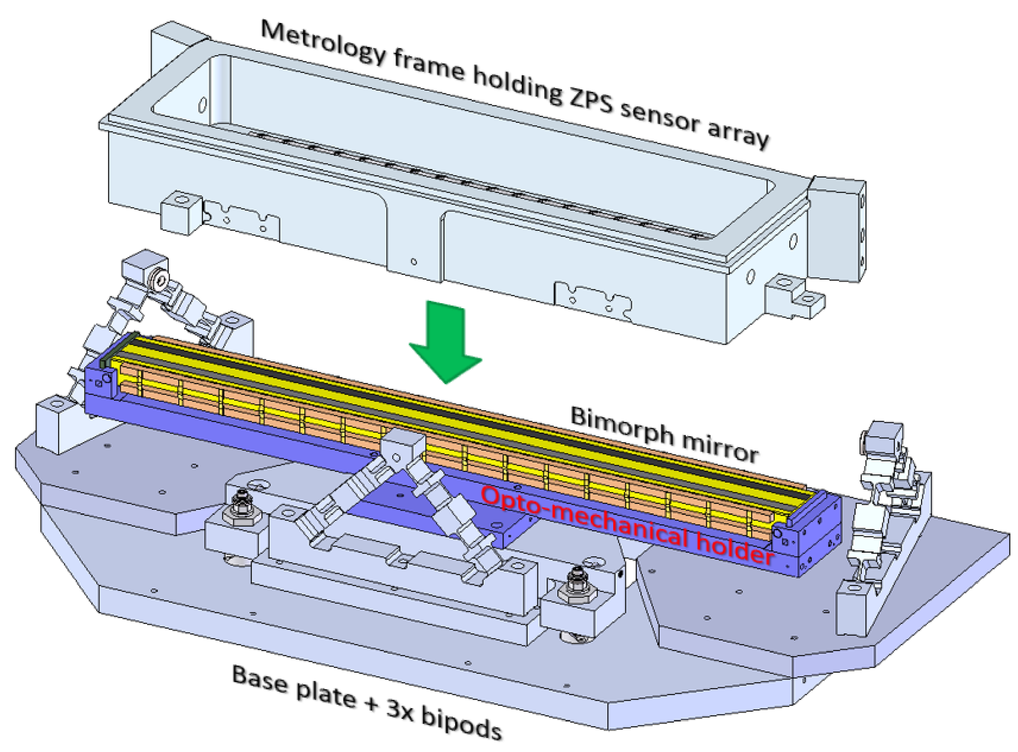
→ Development of high-resolution, real-time, closed-loop "adaptive" optical system for X-ray beamlines [2]

[2] S.G Alcock et al, "Fast shaping control of x ray beams using a closed-loop adaptive bimorph deformable mirror", Optica, 10, 2 (2023) https://doi.org/10.1364/OPTICA.476449

Experimental

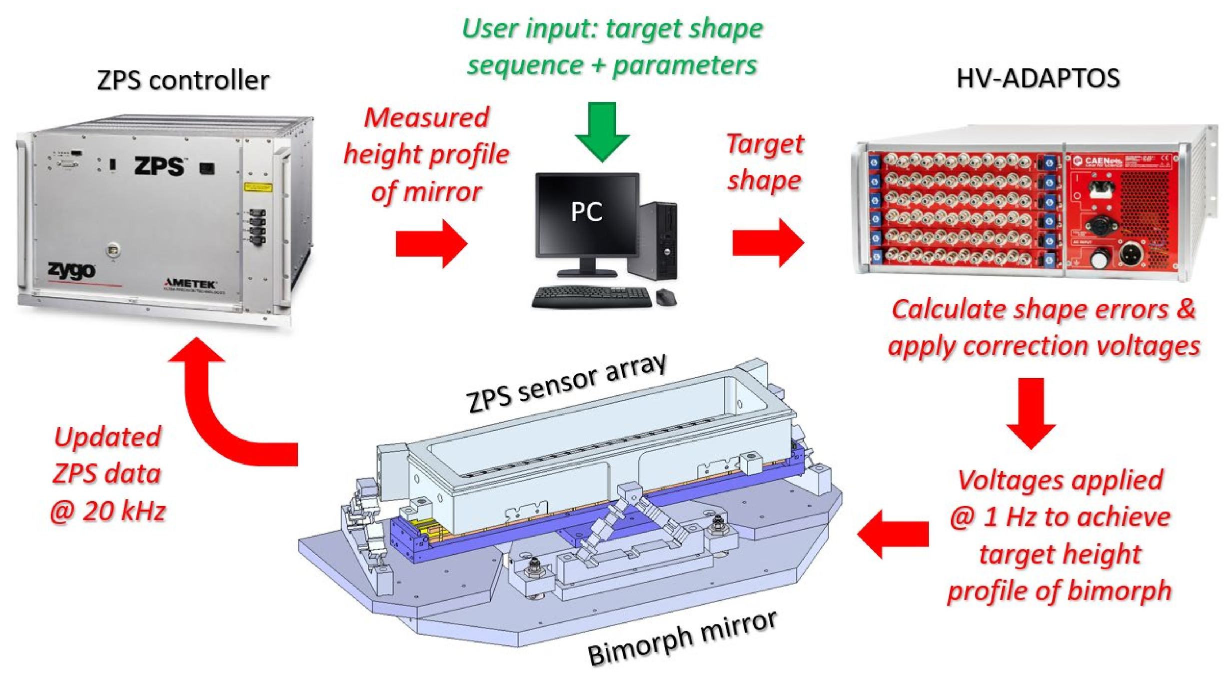
Bimorph mirror & ZPS interferometer system

- 2nd gen. bimorph mirror: 16 piezo electrodes (Thales-SESO)
- Reduced-strain opto-mechanical holder for mirror (Cinel)
- Metrology frame holds ZPS interferometer sensors (Zygo)
- HV-ADAPTOS supplies voltages to piezo electrodes (CAEN)



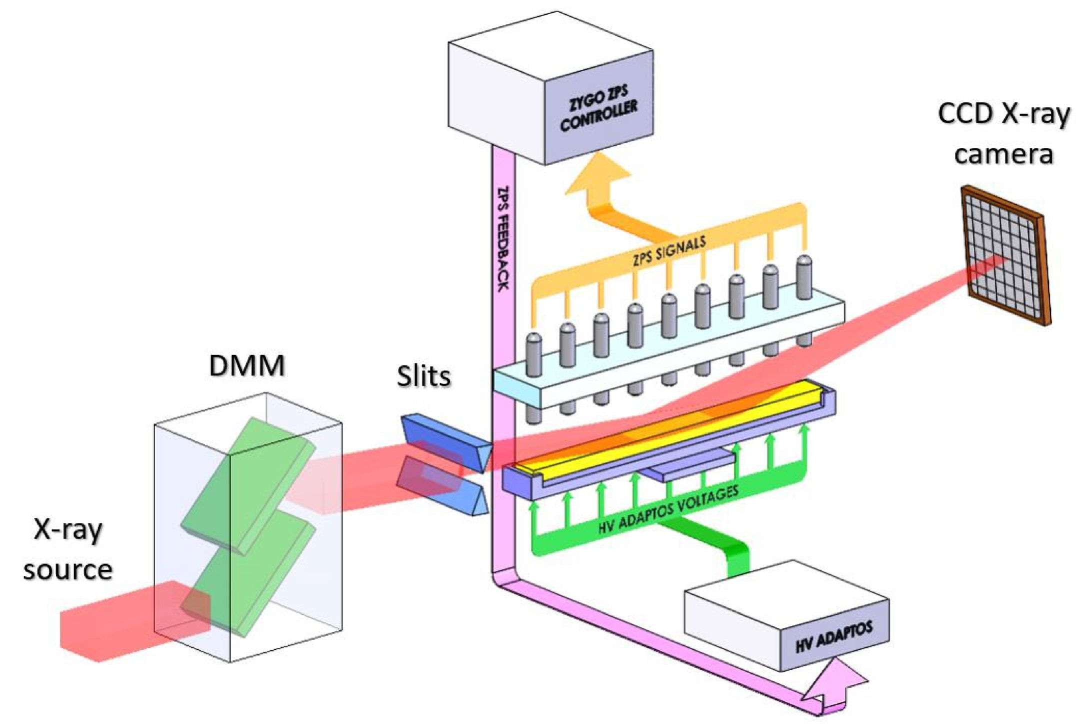
Autonomous closed-loop control

- Height profile of bimorph mirror measured continuously at 20 kHz by 2 x 19 array of ZPS interferometer sensors
- Optical surface data fed to HV-ADAPTOS, which calculates & applies voltages at 1 Hz to null bimorph's surface errors
- User can choose to stabilise mirror at a given curvature, or script changes to occur at specific times



X-ray tests at B16 beamline at Diamond

- Double multilayer monochromator (DMM) selects unfocused monochromatic beam of X-rays (5.5 keV) from "broadband" bending magnet source
- Source to mirror = 43.555 m. Mirror to detector = 3.2 m. Angle of incidence = 3 mrad

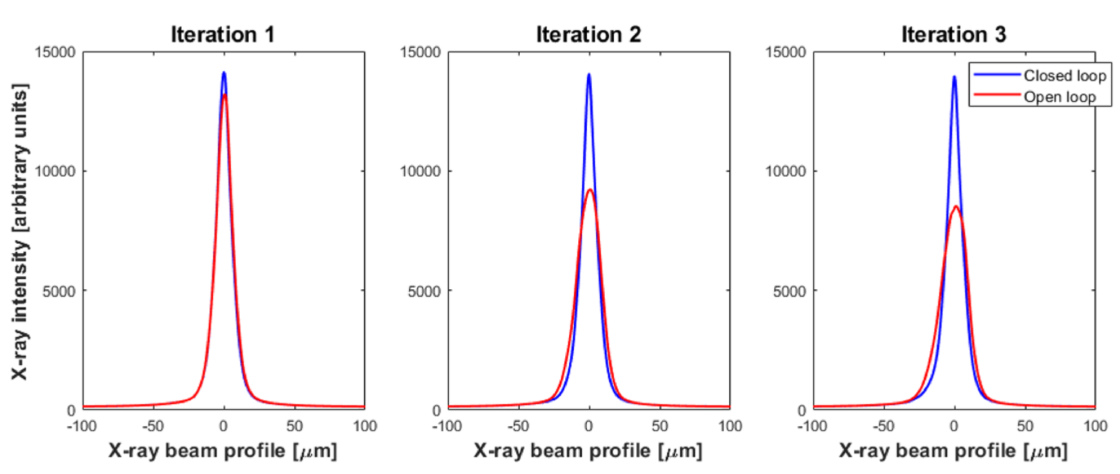


X-ray results

Optimisation of X-ray wavefront

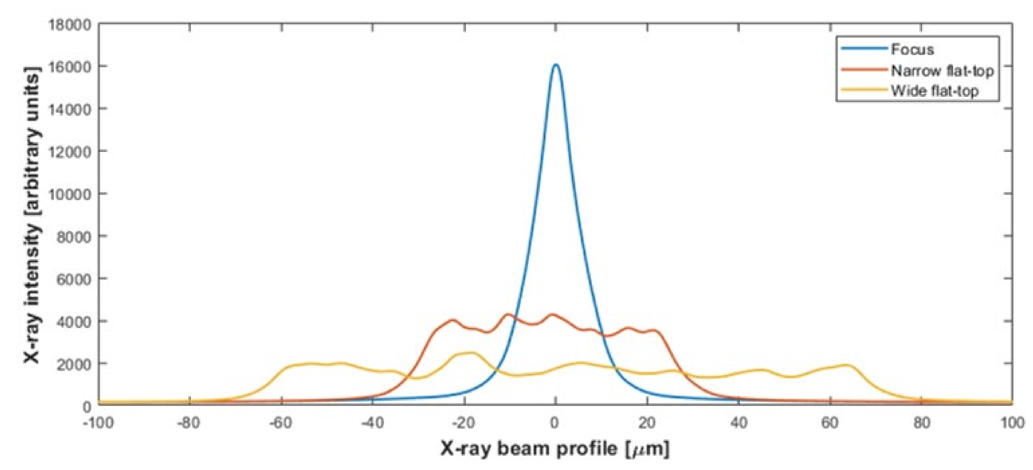
- X-ray speckle scanning (XSS) technique [3] measured reflected X-ray wavefront as voltages sequentially applied to each piezo of bimorph mirror
- Piezo response functions (PRF's) quantify how applied voltages change shape of mirror & modify X-ray wavefront
- Using measured PRFs & wavefront error, voltages are iteratively computed & applied to bend mirror to optimally focus X-ray beam at detector
- Method also corrects wavefront distortions caused by other non-perfect, beamline optics such as DMM

[3] H. Wang, et al, "Advanced in situ metrology for x-ray beam shaping with super precision," Opt. Express 23, 1605–1614 (2015) https://doi.org/10.1364/OE.23.001605

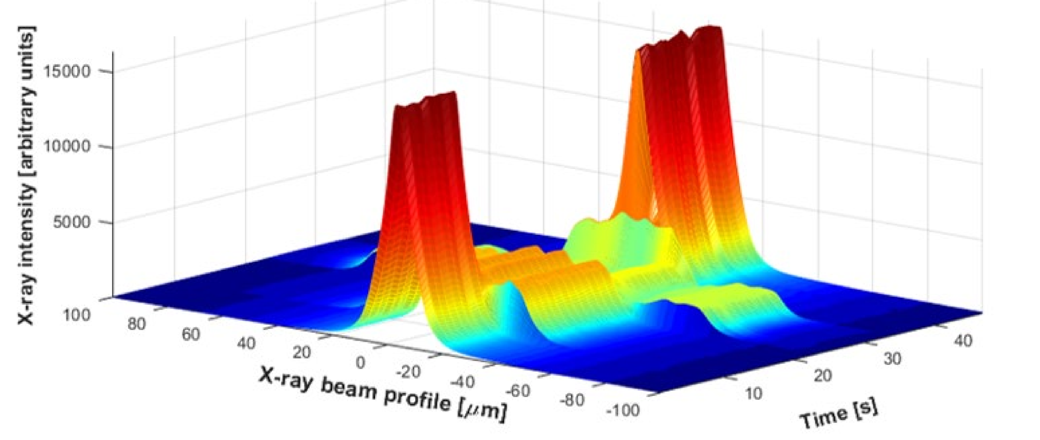


Rapid switch between flat-top X-ray beams

- Focussed X-ray beam converted into constant intensity "flat-top" profiles of user-selectable width

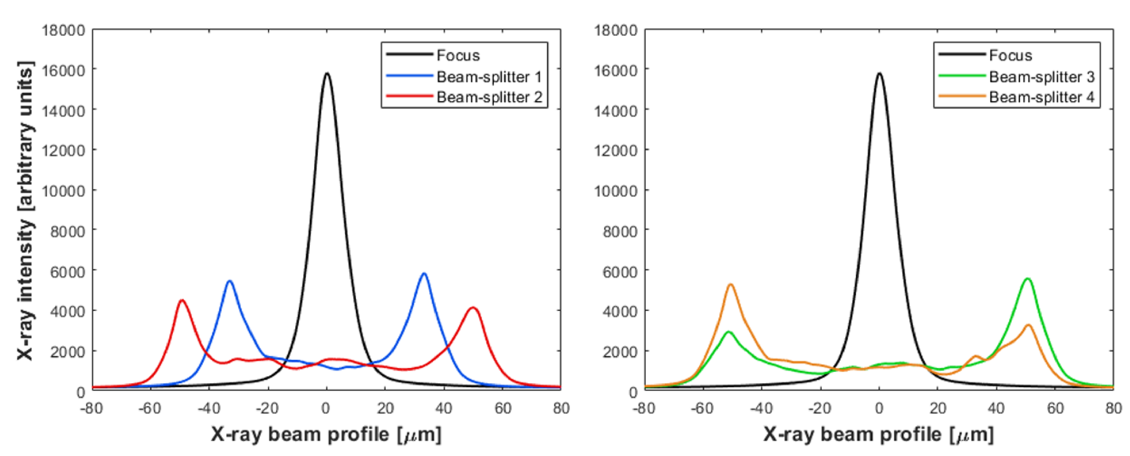


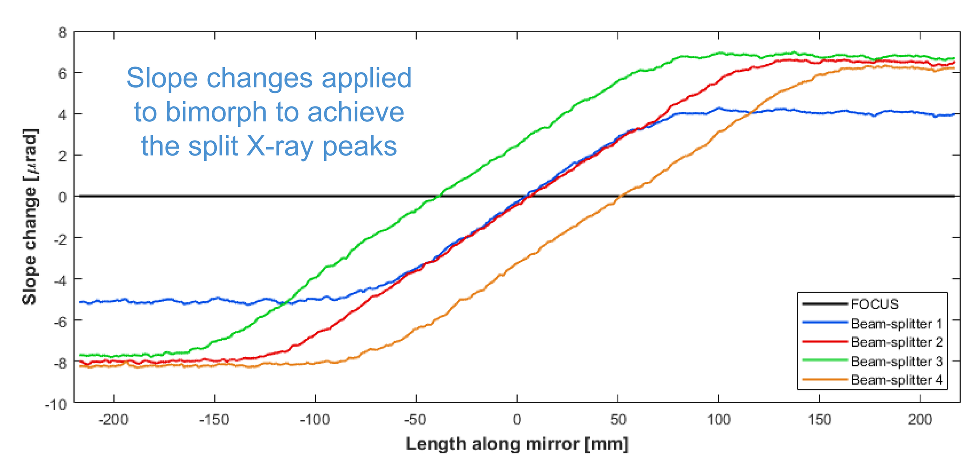
- Width of X-ray beam can be scripted to automatically change at user-defined times (e.g. 10 sec intervals).



Creating split X-ray peaks

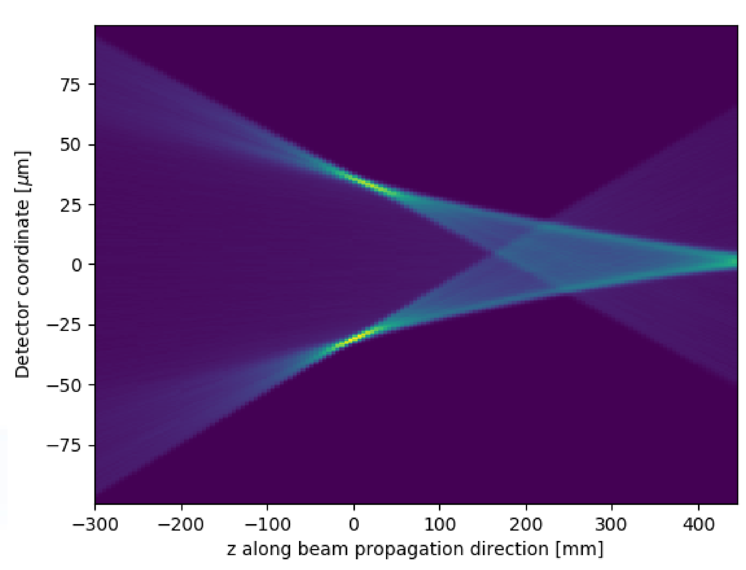
- Focussed X-ray beam (black curve) can be purposefully split into 2 or more side peaks
- Spacing between side peaks (left image), and their relative intensity (right image), can be varied by user
- "Structured light" provides novel illumination of samples





X-ray propagation of split beam

- Ray-tracing simulation (using XRT python package) to investigate how split X-ray beam propagates along beamline's optical axis, Z.
- As anticipated, and observed experimentally, maximum intensity & minimum peak width occur for split peaks at focal plane of CCD detector, $Z = 0$.
- Image generated by integrating X-ray intensity along horizontal plane of detector.



Summary

World 1st "adaptive", automated, closed-loop correction of X-ray bimorph mirror @ 1 Hz

- Multiple ZPS interferometers provide sub-nm feedback for correction of optical surface
- Prototype successfully tested in Optics Metrology Lab & operated on B16 Test beamline
- Demonstration of autonomous, non-invasive, control of size & shape of reflected X-ray beam
- Closed-loop can switch & stabilize between range of X-ray wavefronts, including flat-top beams or splitting X-ray beam into multiple peaks with user-definable separation & relative magnitude

For further details, please contact: simon.alcock@diamond.ac.uk or ioana.nistea@diamond.ac.uk

diamond