Argonne NATIONAL LABORATORY

Precision Mechanical Design of a Miniatire Dynamic Mirror Bender for the SSRF Beamline Upgrade Project

Deming Shu

Advanced Photon Source, Argonne National Laboratory
Argonne, IL 60439, U.S.A.

With my colleagues at
[1]Advanced Photon Source, ANL, Argonne, IL 60439, USA
[2]Shanghai Synchrotron Radiation Facility, SINAP, Shanghai 201204, China
[3]University of Illinois at Chicago, Chicago, IL 60607, USA

Aiguo Li[2], Steven P. Kearney[1], Chengwen Mao[2], Jayson Anton[1,3], and Yaolin Pan[2]

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U.S. DEPARTMENT OF ENERGY

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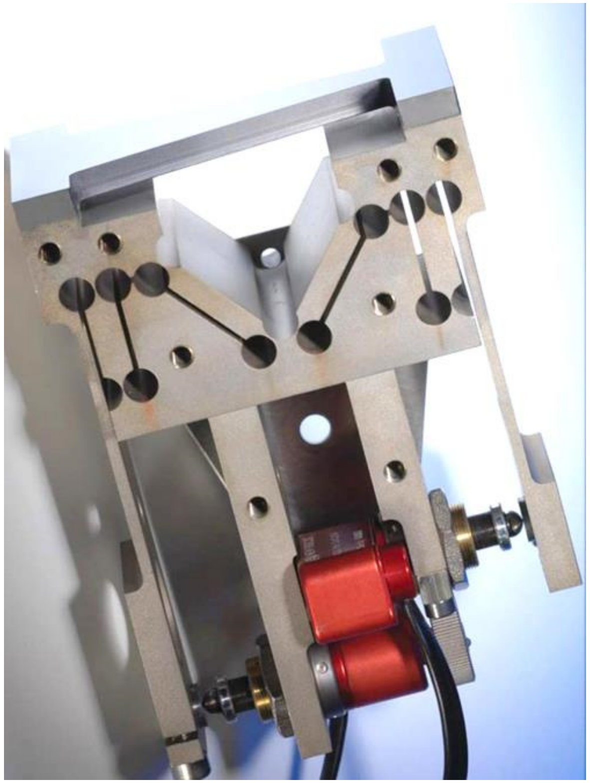
Introduction

- The Shanghai Synchrotron Radiation Facility (SSRF) is a 3.5 GeV third generation synchrotron radiation source. Currently, there are sixteen more beamlines under design and construction stage for the SSRF Phase-II beamline construction project.
- Both SSRF and Advanced Photon Source (APS) have a keen interest in the development of novel K-B mirror mount stages for synchrotron radiation applications.
- As a part of Argonne Strategic Partnership Project (SPP) (formerly known as work for others or WFO project), collaboration between Argonne National Laboratory (ANL) and Shanghai Institute of Applied Physics (SINAP) has produced designs of a new miniature dynamic mirror bender using Argonne's laminar nanopositioning flexure technique for the beamline upgrade project at the SSRF.
- The motivation of the new design is to develop a compact, cost-effective flexure mirror bender with high stability.

Introduction

- **Dynamic mirror benders which enable high precision figuring of planar substrates for x-ray focusing are widely used as conventional optical equipment in various synchrotron radiation beamlines.**
- **Especially, in cases for x-ray focusing optics coated with multilayers in a Kirkpatrick-Baez (K-B) configuration [1] as the final focusing elements immediately upstream of the sample, the dynamic mirror benders provide high precision figuring to allow the mirror figure to be tuned to optimize the focusing at different incidence angles to cover a wide energy range [2].**



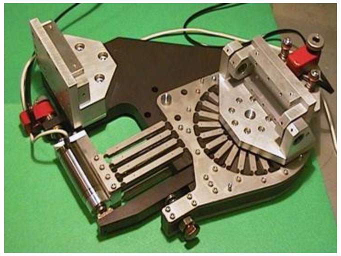
Courtesy of Dr. R. Barrett, ESRF

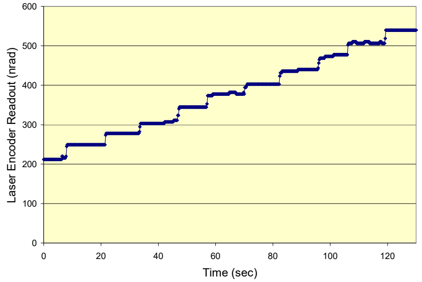
[1] Kirkpartrick, P. and Baez, A. V. Formation of Optical Images by X-Rays. JOSA. 1948; 38(9): 766-773.
[2] R. Barrett, J. Härtwig, C. Morawe et al, Synchrotron Radia-tion News, 23, No.1, 36-42 (2010)

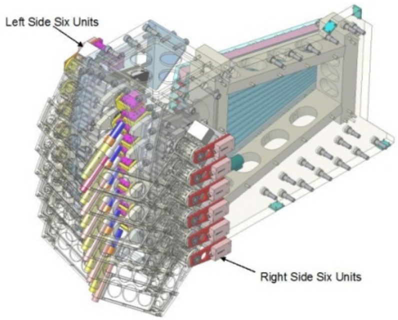
Introduction

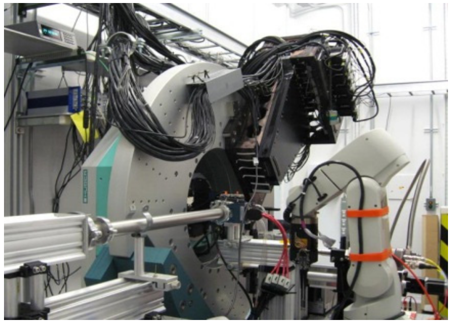
Nanopositioning development at the APS

Rotary weak-link mechanism applications

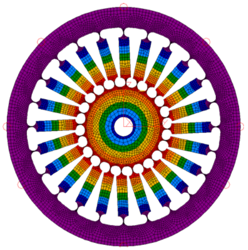


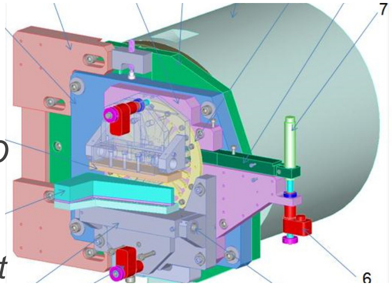






Twelve-analyzer detector system for high-resolution powder diffraction (11-BM)





A 3D model of the 15-ID artificial channel-cut crystal stage for the APS USAXS instrument crystal analyzer system

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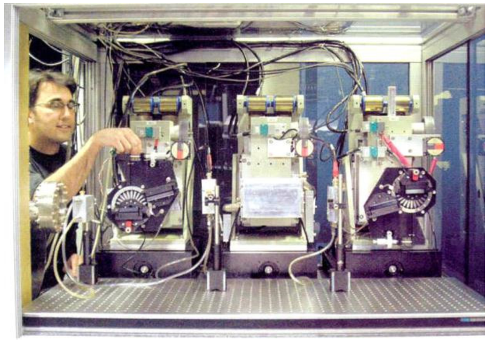
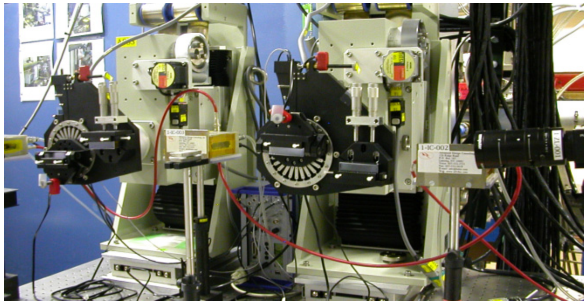
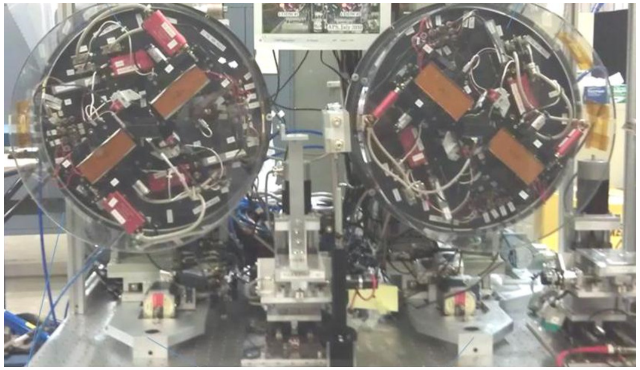


High-energy-resolution hard x-ray monochromators (3-ID)



High-energy x-ray monochromator (1-ID-B)



CDFDW prototype (30-ID)

References:

D. Shu, T. S. Toellner, and E. E. Alp, "Modular Overconstrained Weak-Link Mechanism for Ultraprecision Motion Control," Nucl. Instrum. Methods A 467-468, 771-774 (2001).

U.S. Patent granted No. 6,607,840, Redundantly constrained laminar structure as weak-link mechanisms, D. Shu, T. S. Toellner, and E. E. Alp, 2003.

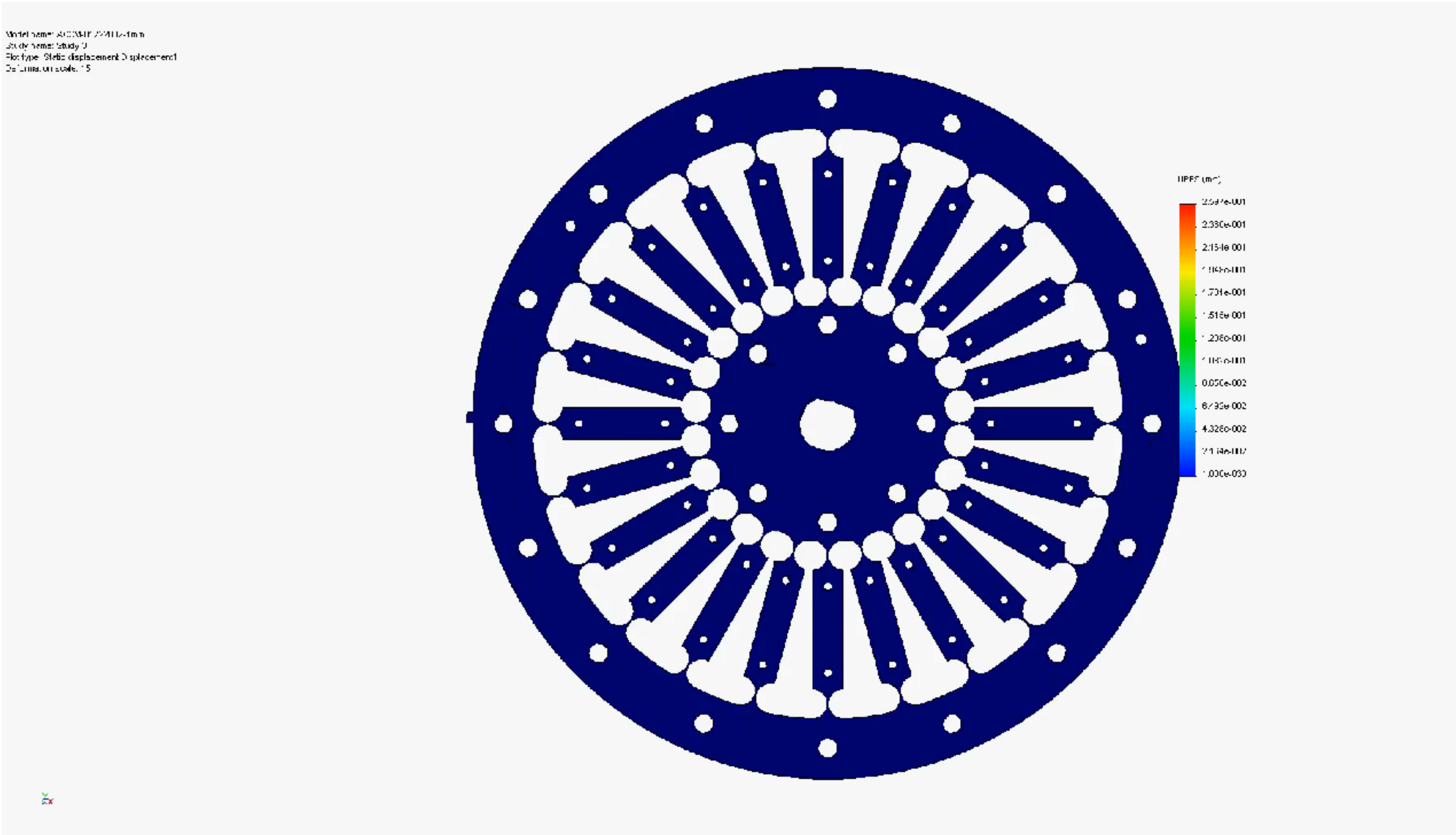
D. Shu, T. S. Toellner, E. E. Alp, J. Maser, J. Ilavsky, S. D. Shastri, P. L. Lee, S. Narayanan, and G. G. "Applications of Laminar Weak-Link Mechanisms for Ultraprecision Synchrotron Radiation Instruments", AIP CP879, 1073-1076 (2007).

B. Jakobsen, H. F. Poulsen, U. Lienert, J. Almer, S. D. Shastri, H. Sorensen, C. Gundlach, W. Pantleon, Science 312, 889-892 (2006).

Y. Shvyd'ko et al., Nature Commun. 5, 4219 (2014). DOI:10.1038/ncomms5219.

Introduction

Weak-link-based Artificial Channel-Cut Crystal Mechanism



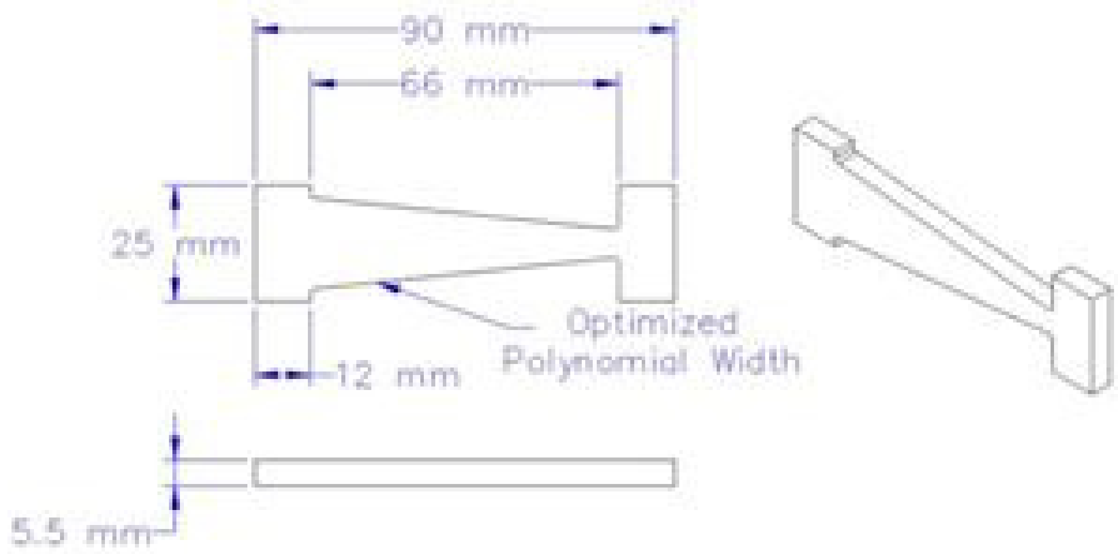
[3] U.S. Patent granted No. 6,607,840, D. Shu, T. S. Toellner, and E. E. Alp, 2003.

[4] U.S. Patent granted No. 6,984,335, D. Shu, T. S. Toellner, and E. E. Alp, 2006.

[5] D. Shu, T. S. Toellner, E. E. Alp, J. Maser, J. Ilavsky, S. D. Shastri, P. L. Lee, S. Narayanan, and G. G. Long, AIP CP879, 1073-1076 (2007)

Test Mirror for Prototype

- **The 90 mm long silicon mirror has an effective optical length of 66 mm and thickness of 5.5 mm.**
- **The width of the mirror is designed to perform the optical figuring of the mirror under bending [6].**
- **With a dynamic mirror bender, which is capable to provide bent moment tuneable between 0.35 N·m to 0.71 N·m, the elliptical mirror figure radiuses are tuneable between of curvatures of 24 m–88 m to 12 m-44 m.**



[6] A. Li and C. Mao, Private Communications (2016)

Design of the Mirror Bender

Based on the type of bending actuators, the miniature dynamic mirror bender is designed with two configurations:

- **The open-loop control configuration with Newport™ Picomotor™ actuators**
- **The closed-loop control configuration with Newport™ NPM-140 piezo micrometer adapter [7].**

Both design configurations use the same flexure bending mechanism module.

[7] http://www.newport.com/Picomotor-Piezo-Linear-Actuators/

Design of the Mirror Bender

Mirror Bender with Newport™ Picomotor™ Actuators

The miniature dynamic mirror bender for open-loop control configuration consists of:

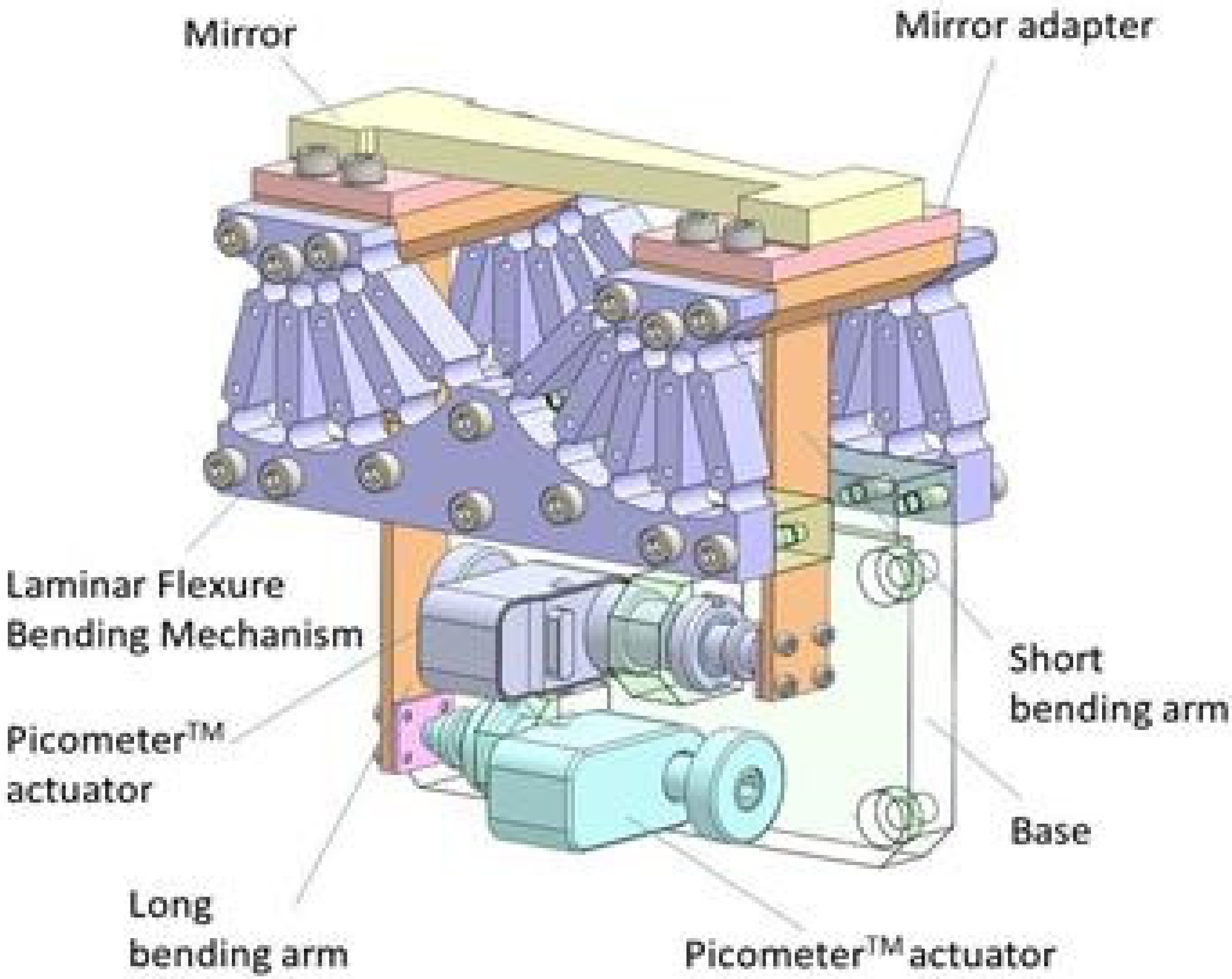
- **a base;**
- **a pair of laminar flexure mechanism modules;**
- **a pair of bending arms;**
- **two Newport™ Picomotor™ 8301 actuators.**

The silicon mirror is bonded to a pair of adapters to connect with the bender.

Since the PicomotorTM 8301 piezo linear actuator has a limited 22 N axial load capacity, similar to the ESRF mirror bender design [2], the bender has a longer bending arm to provide the necessary bending moment. The elastic deformation of the bending arm also provides an extended bending resolution.

Design of the Mirror Bender

Mirror Bender with Newport™ Picomotor™ Actuators



Design of the Mirror Bender

Mirror Bender with Newport™ NPM-140 Piezo Micrometer Adapter

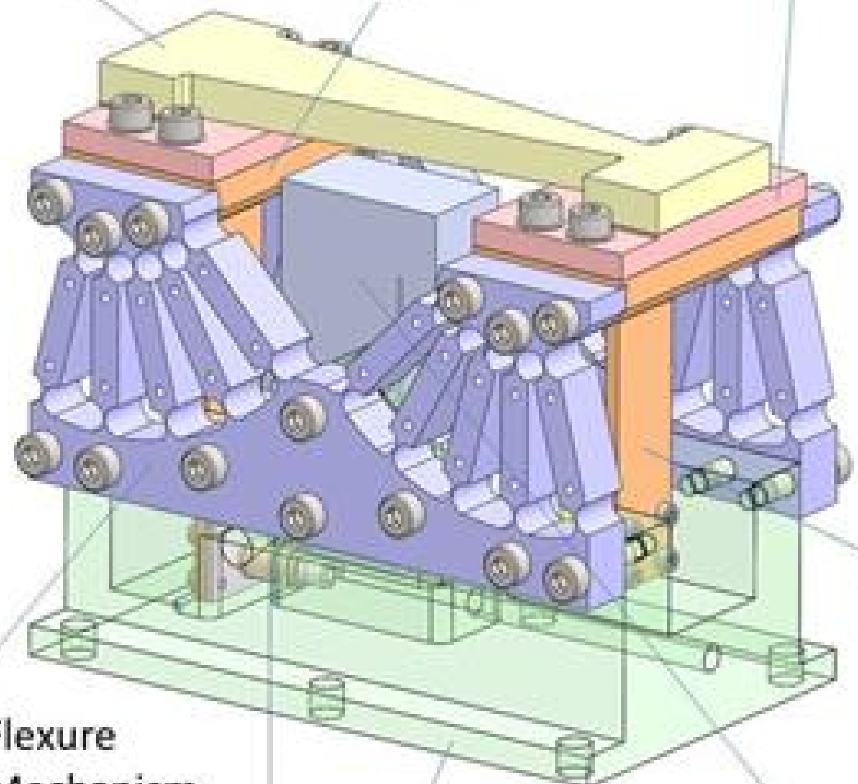
With Newport™ NPM-140 piezo micrometer adapter's 100 N axial load capacity and nanometer-scale positioning resolution [7], the dynamic mirror bender's closed-loop control configuration also has a more compact design with shorter bending arm. The closed-loop control configuration consists of:

- **a base;**
- **a pair of laminar flexure mechanism modules;**
- **a pair of bending arms;**
- **a Newport™ NPM-140 piezo micrometer adapter with 140 micron travel range for the long bending arm;**
- **two manual adjusters for both long and short bending arms.**

Design of the Mirror Bender

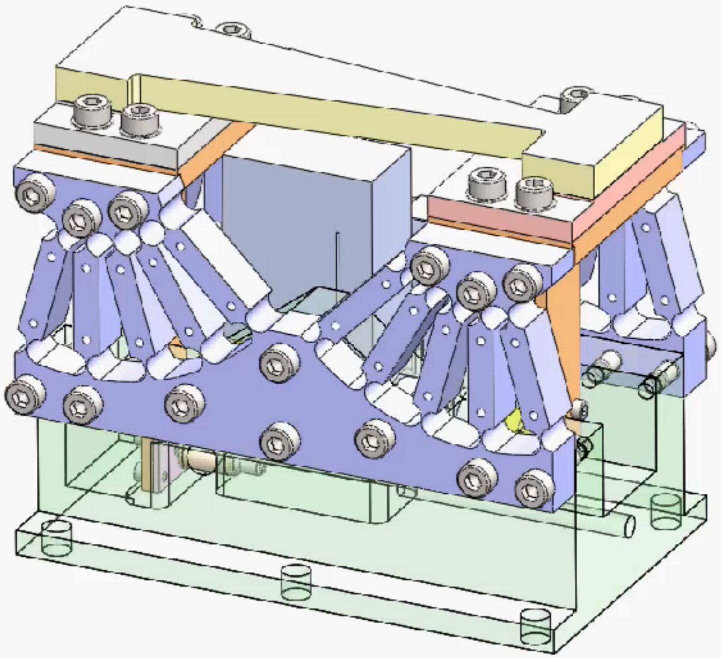
Mirror Bender with Newport™ NPM-140 Piezo Micrometer Adapter

Courtesy of Newport Co.



Design of the Mirror Bender

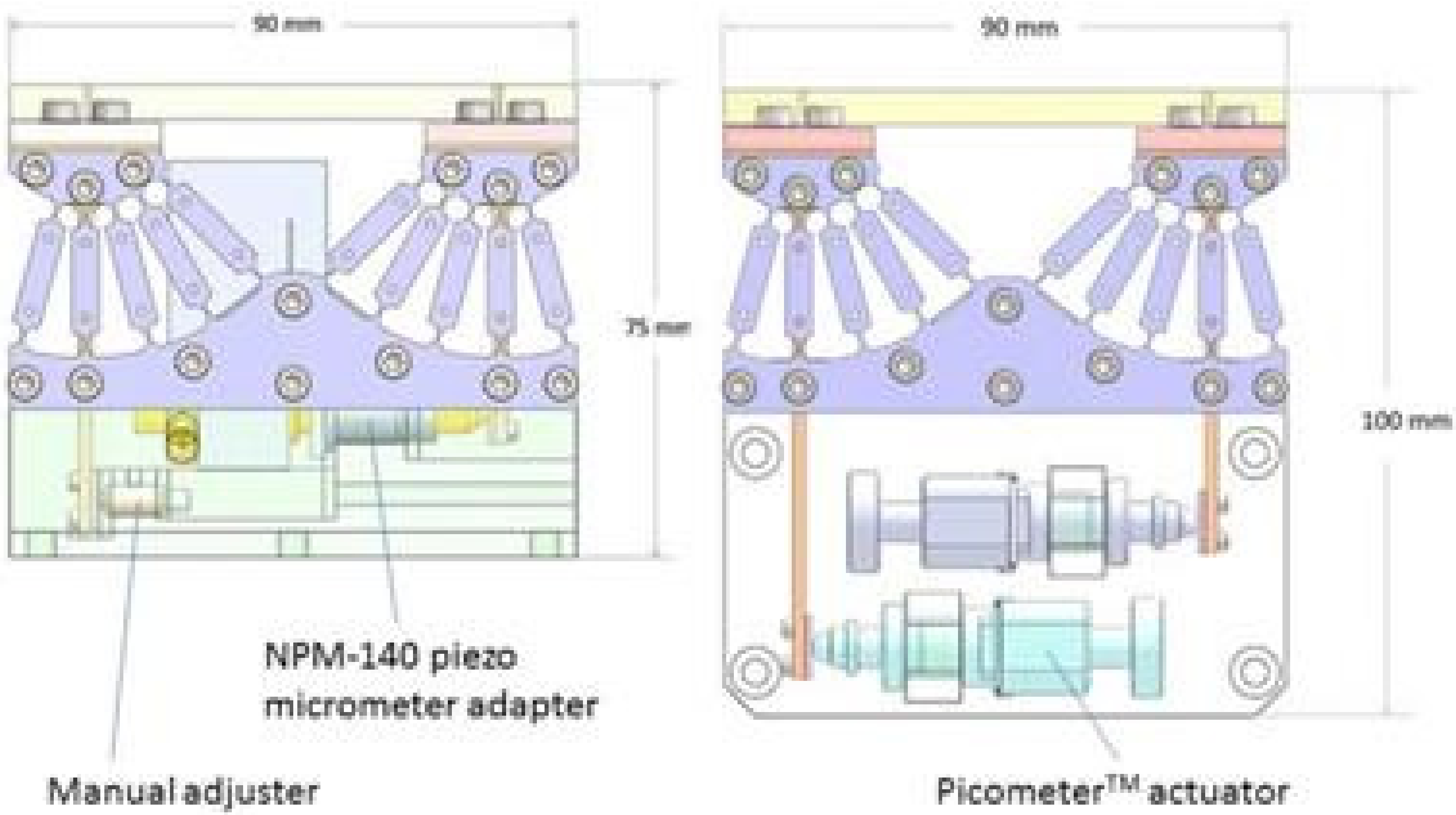
Mirror Bender with Newport™ NPM-140 Piezo Micrometer Adapter



Design of the Mirror Bender

Comparison between the two configurations of the dynamic mirror bender design.

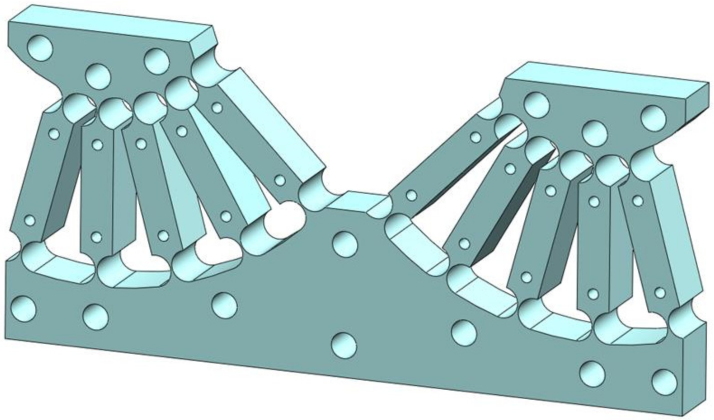
The configuration with NewportTM NPM-140 piezo micrometer adapter shows a 25% overall height reduction.



Design of the Mirror Bender

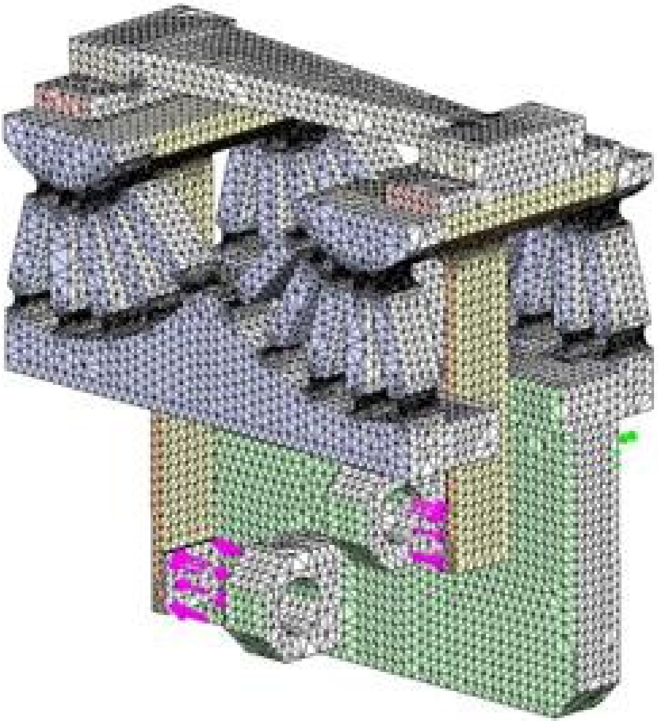
Design of Laminar Flexure Bending Mechanism

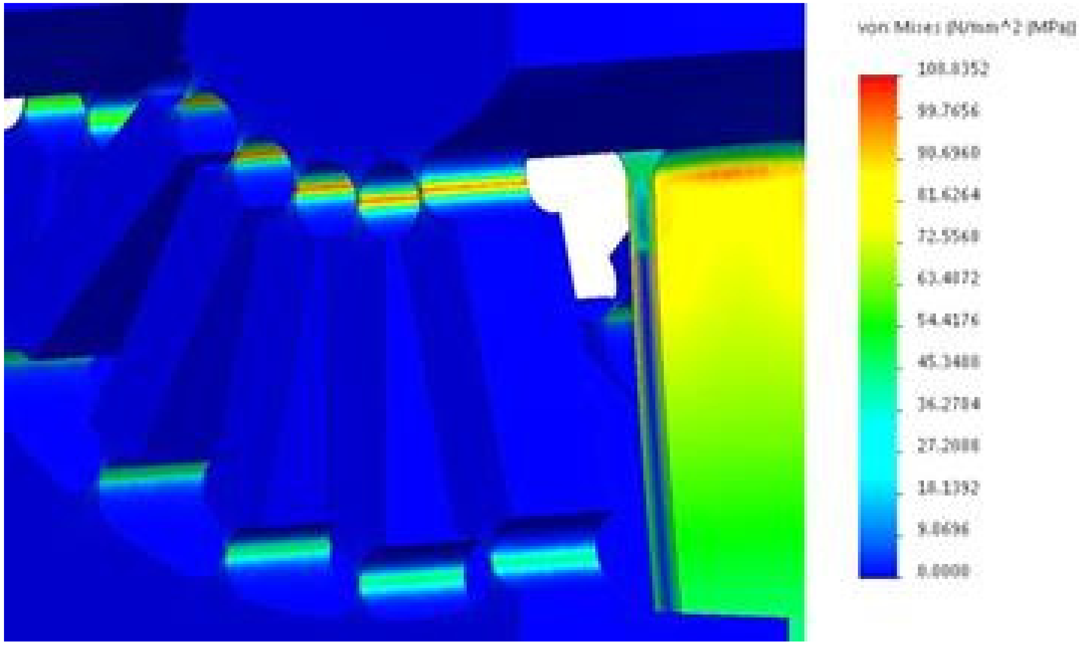
- The flexure bending mechanism module is constructed with stacks of thin metal weak-link sheets which are manufactured using photochemical machining processes with lithography techniques [4].
- The module is a solid laminar bonded complex structure designed for ultrahigh positioning sensitivity and stability performance.
- It is a combination of two individual tip-tilting flexural guiding structures.
- The 8-mm-thick bonded module consists of forty layers of 200-micron-thick photochemical machined single weak-link sheet.
- The weak-link sheet material could be 17-7 PH stainless steel (for lager dynamic range) or Invar-36 (for better thermal stability).



Prototype for Finite Element Analysis and Preliminary Test

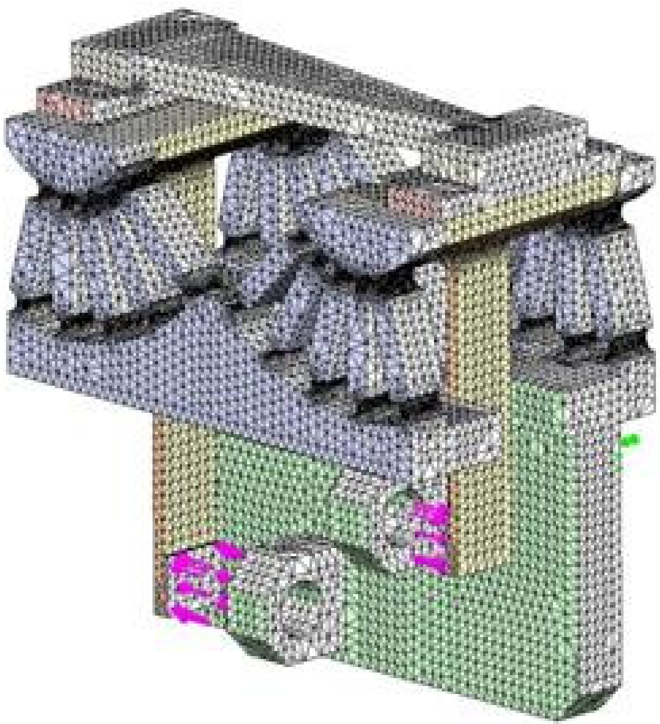
Finite element analysis (FEA) results for the Z7-5006 dynamic mirror bender prototype with open-loop control configuration show that, with a 15.1 N load applied to the short bending arm and a 11.4 N load applied to the long bending arm (to simulate a bent moment of ~1 N·m), the maximum Von-Mises stress on the 8-mm-thick weak-link modules reaches ~109 MPa, which is only less than 10% of the material yield stress for 17-7-PH stainless steel.

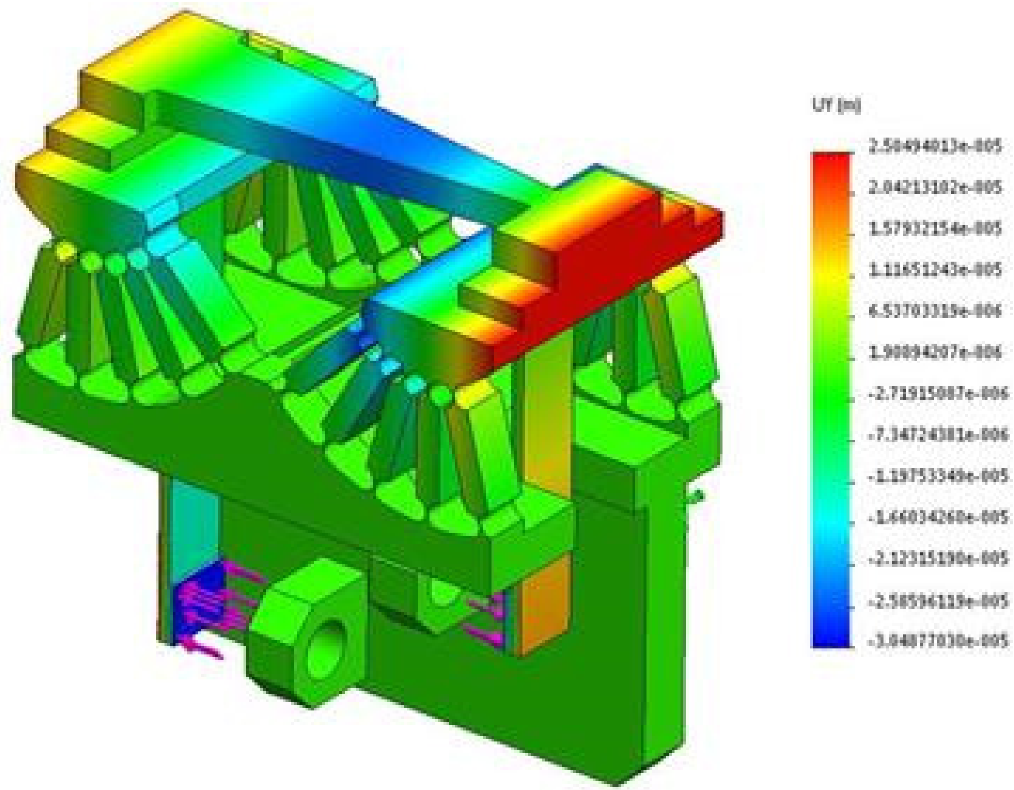




Prototype for Finite Element Analysis and Preliminary Test

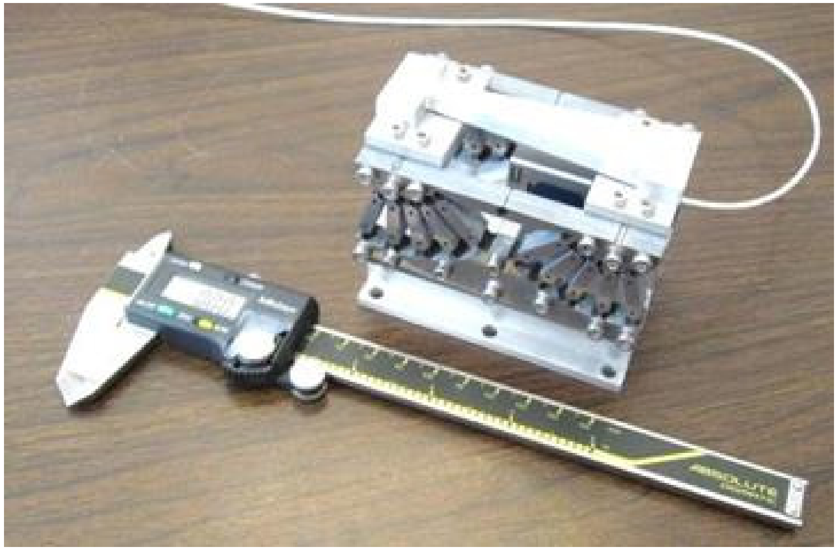
Finite element analysis (FEA) results for the Z7-5006 dynamic mirror bender prototype with open-loop control configuration show that, with a 15.1 N load applied to the short bending arm and a 11.4 N load applied to the long bending arm (to simulate a bent moment of ~1 N·m), The maximum displacement of the long bending arm is ~0.97 mm. The maximum displacement of the short bending arm is ~0.57 mm.

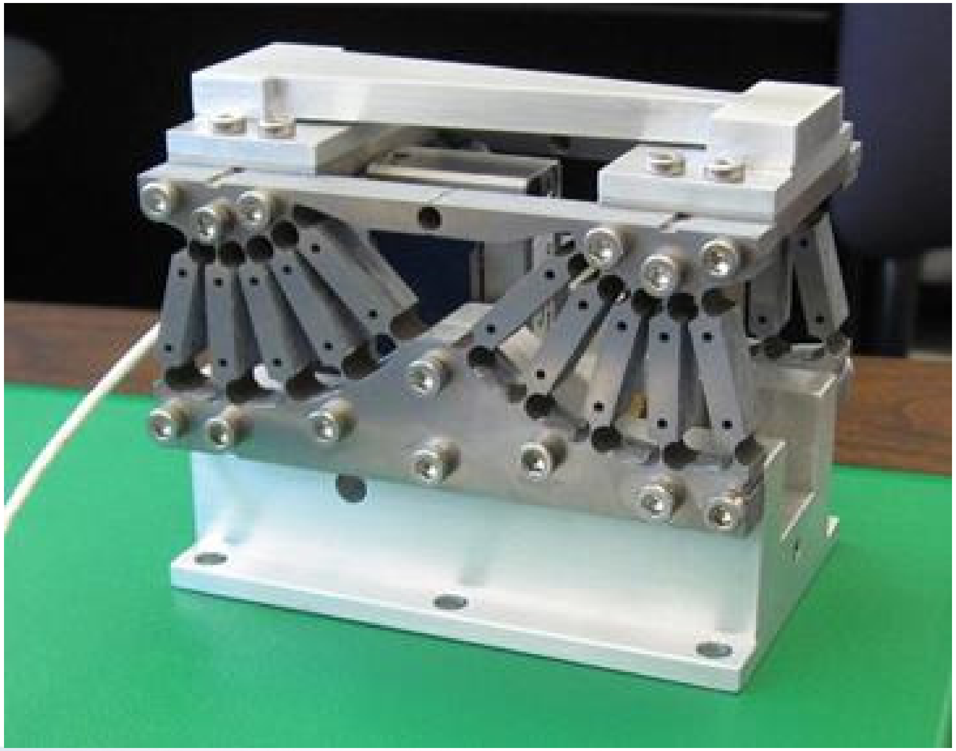




Prototype for Finite Element Analysis and Preliminary Test

A prototype of the miniature dynamic mirror bender Z7-5006 with closed-loop control configuration has been designed and constructed for preliminary mechanical and optical tests. An aluminium alloy dummy mirror with mirror adapter is mounted on the dynamic mirror bender for mechanical assembly test. The flexure bending mechanism module is constructed with 17-7 PH stainless steel sheet. The material used for the short and long bending arms is Invar-36. The proto-type's base is made from aluminium alloy.
Temporary linkages between the two individual tip-tilting flexural guiding structures in the module have not been removed yet.





Summary

- The mechanical design of a miniature dynamic mirror bender with open-loop control and closed-loop control configurations for beamline upgrade project at the SSRF are presented in this paper.

- FEA results have shown that the mechanical design of the Z7-5006 prototype bender is capable of meeting design requirements for the SSRF 90-mm-long test mirror.

- Table 1 summarizes the design specifications of the Z7-5006 prototype miniature dynamic mirror bender.

- Mechanical test with laser interferometer is in progress. The results will be presented in a separate paper later.

Summary

Table 1: Design specifications of the Z7-5006 prototype miniature dynamic mirror bender

Z7-5006 dynamic mirror bender (open-loop control configuration)	
Overall dimensions (mm)	90 (L) x 62 (W) x 100 (H)
Normal load capacity (kg)	0.1
Driver type	Newport™ Picomotor™ linear actuator
Driver encoder type	N/A
Driver axial load capacity (N)	22
Driver min. incremental (nm)	20
Manual adjustment option	Yes
Tuneable bent moment (N·m)	0.2 - 1
Z7-5006 dynamic mirror bender (closed-loop control configuration)	
Overall dimensions (mm)	90 (L) x 62 (W) x 75 (H)
Normal load capacity (kg)	0.1
Driver type	Newport™ NPM-140 piezo micrometer adapter with closed-loop control option
Driver encoder type	strain-guage
Driver axial load capacity (N)	100
Driver closed-loop travel range (micron)	140
Driver min. incremental (nm)	1
Manual adjustment option	Yes
Tuneable bent moment (N·m)	0.2 - 1

Acknowledgment

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Thank You for Your Attention