ISBN: 978-3-95450-207-3 doi:10.18429/JACoW-MEDSI2018-WEOPMA04

MECHANICAL DESIGN OF A NEW PRECISION ALIGNMENT APPARATUS FOR COMPACT X-RAY COMPOUND REFRACTIVE LENS MANIPULATOR*

D. Shu†, Z. Islam, J. Anton[1], S. Kearney, X. Shi, W. Grizolli, P. Kenesei, S. Shastri, L. Assoufid
Advanced Photon Source, Argonne National Laboratory, Argonne, IL, USA
[1]University of Illinois at Chicago, Chicago, IL, USA

Abstract

A prototype of compact x-ray compound refractive lens (CRL) manipulator system has been developed at the Argonne National Laboratory for dark-field imaging of multi-scale structures. This novel full-field imaging modality uses Bragg peaks to reconstruct 3D distribution of mesoscopic and microscopic structures that govern the behavior of functional materials, in particular, thermodynamic phase transitions in magnetic systems. At the heart of this microscopy technique is a CRL-based x-ray objective lens with an easily adjustable focal length to isolate any region of interest, typically in the energy range of 5-100 keV or higher, with high precision positional and angular reproducibility. Since the x-ray CRL manipulator system for this technique will be implemented on a high-resolution diffractometer detector arm that rotates during diffraction studies, compactness and system stability, along with the ability to change focal length ("zooming"), became key design requirements for this new CRL manipulator system. The mechanical designs of the compact x-ray CRL manipulator system, as well as finite element analysis for its precision alignment apparatus are described in this paper.

INTRODUCTION

The macroscopic properties of functional materials (including most technologically relevant properties) are controlled by microscopic and nano-scale features and processes. It is important to deepen our understanding of couplings between such multi-scale structural features (e.g. as twin boundaries, grain orientations, lattice distortions, or magneto-striction) and average materials properties (thermodynamic, magneto-caloric, pinning, transport, critical current, etc.) as well as order parameters. Furthermore, the nature of hysteretic magnetic and/or structural transitions and related phenomena (e.g. memory effects, domain network, fluctuations, and relaxation) tuned in by magnetic fields at cryogenic temperature is of great interest. So, there is a growing need, especially in the wake of near diffraction-limited sources being on the horizon, to develop imaging techniques ideally suited for problems alluded to above and to complement well-known resonant and non-resonant diffraction methods.

While there is a plethora of x-ray microscopy techniques that are poised to provide high-resolution real-space images of inhomogeneous materials at multiple length scales and their evolution through phase transi-tions, dark-field x-ray microscopy (DFXM) stands out as a fast imaging method [1-6]. This full-field imaging modality uses Bragg peaks to reconstruct 3D distribution of mesoscopic and microscopic structures in materials. A Bragg peak is excited and its intensity distribution is recorded using an area detector. However, the diffracted beam is passed through an x-ray objective lens to magnify and project onto a scintillator before detection with a high-resolution CCD camera. The key is to collect diffraction data of a particular Bragg peak as the sample is rotated around the momentum transfer, with a high precision, over a range of full 360º.

A CRL-based x-ray objective lens [7-9] with an easily adjustable focal length to isolate any region of interest is a central piece of this microscopy technique. For such application CRL-based x-ray objective lens operating over a wide energy range (e.g. 5-100 keV, or even higher), with high precision positional and angular reproducibility, need to be implemented on a high-resolution diffractometer detector arm that rotates during diffraction studies. As such, compactness and system stability, along with the ability to change focal length, became key design re-quirements for this new CRL manipulator system.

In this paper, we present a proof-of-principle prototype design for the compact x-ray CRL manipulator along with its preliminary x-ray test results first, followed by the designs of the manipulators for 16-mm- and 32-mm-long CRL stacks, and conclude with the design options of the CRL manipulators integration.

PROOF-OF-PRINCIPLE PROTOTYPE

The novelty of the new mechanical design is the compactness and positioning stability as well as repeatability of its unique flexural lens holder alignment structure. It is using commercial high precision V-rail for linear roller bearing [10] as a reference base.

Figure 1 shows a 3D-model of the prototype for demonstrating proof-of-principle of operation. As shown in Fig. 1, the prototype CRL manipulator includes a base subassembly with stage support and a base V-rail, a lens holder V-rail with lens holder frame subassembly, a commercial miniature piezo-driven linear stage (SmarActTM 1720s) [11], and a multi-dimensional flexural link subassembly. As shown in Fig. 2, a group of eight CRL is confined by a thin metal lens confiner, which is mounted on the bottom of the lens holder frame. A short linear bearing V-rail is

* Work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.
† shu@aps.anl.gov

ISBN: 978-3-95450-207-3 doi:10.18429/JACoW-MEDSI2018-WEOPMA04

mounted in the lens holder frame as the top half of the lens alignment structure. At the linear stages lower limit position, the flexural link subassembly, as shown in Fig. 3, provides multi-dimensional flexibility to ensure the CRL group to be fully aligned between the lens holder V-rail and the base V-rail.

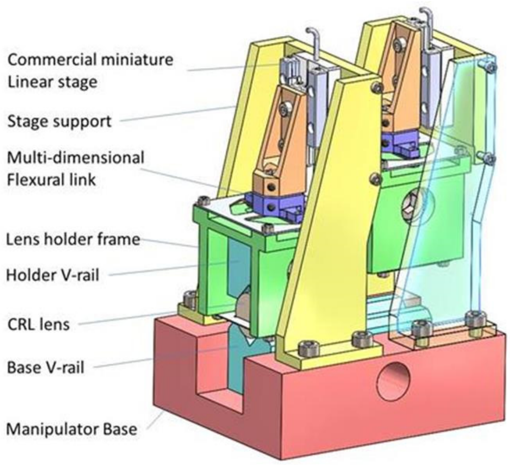

Figure 1: A 3-D model of the proof-of-principle prototype design for the compact x-ray CRL manipulator.

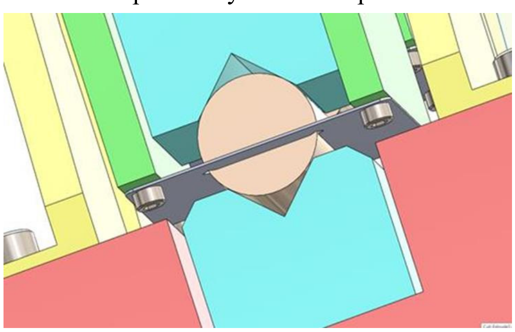

Figure 2: A 3-D model of the eight CRL confined by a thin metal lens confiner, which is mounted on the bottom of the lens holder frame.

X-RAY TEST FOR THE PROOF-OF-PRINCIPLE PROTOTYPE

A proof-of-principle prototype for the compact x-ray CRL manipulator was manufactured with 3D-printing technique as shown in Fig. 4. It is designed to hold a group of eight 2-D parabolic beryllium CRL lenses with 50 micron radius of curvature from RXOPTICSTM. The 2D-lenses have a circular frame with a diameter of 12 mm and a thickness of 2 mm for each lens. The x-ray test was performed at the APS 1-BM beamline using an 8 keV beam. The measured focal size of the lens stack is 4.1x1.7 µm2 FWHM at 589 mm downstream of the lens stack as shown in Figs. 5 and 6. The total transmission of the stack is 36% within the 390×390 µm2 aperture, which gives a gain of ~8000.

The repeatability of the prototype manipulator was tested by moving the lens stack up and down. No measureable difference was observed. A second stack of 8 lenses was tested as well with a similar measured focal size. It indicates a good quality consistency of these lenses.

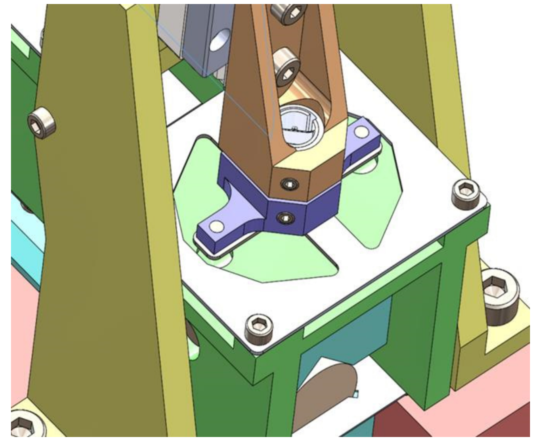

Figure 3: A 3-D model of the multi-dimensional flexural link subassembly which links the lens holder frame with the carriage of the miniature piezo-driven linear stage.

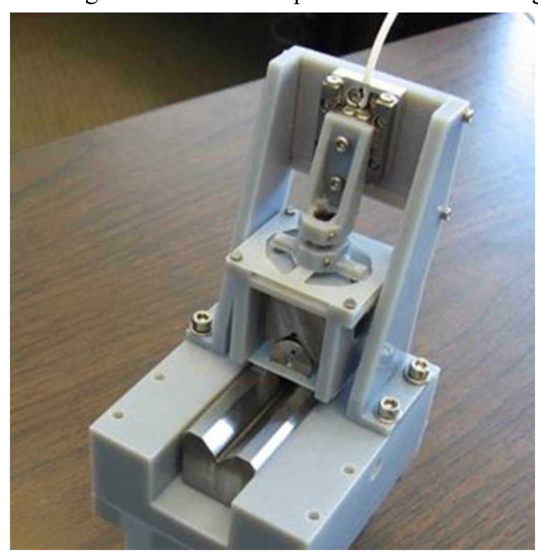

Figure 4: Photograph of the proof-of-principle prototype for the compact x-ray CRL manipulator manufactured with 3D-printing technique and modified commercial THK™ linear bearing V-rail.

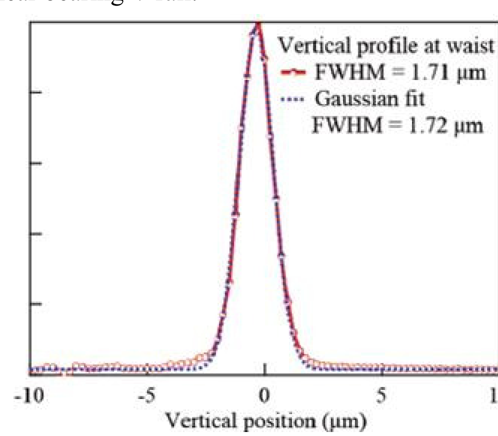

Figure 5: The measured vertical focal size of the lens stack is 1.7 µm FWHM at 8 keV.

ISBN: 978-3-95450-207-3 doi:10.18429/JACoW-MEDSI2018-WEOPMA04

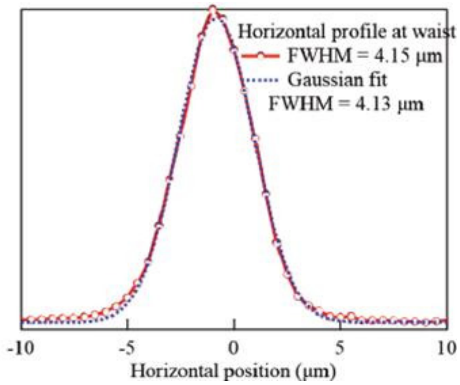

Figure 6: The measured horizontal focal size of the lens stack is 4.1 μm FWHM at 8 keV.

DESIGN OF THE COMPACT MANIPULATOR FOR 16-MM CRL LENS STACK

Based on the experiences gained from the proof-of-principle prototype, a compact manipulator APS Y9-5101 for 16-mm CRL lens stack was designed using commercial miniature piezo-driven linear stage, such as SmarAct™ 1720s, as a lens manipulating driver. As shown in Fig. 7, a group of four Y9-5101 CRL manipulators are mounted on a pair of linear guiding rails and linked together as a unit to be driven by a manual or motorized linear motion driver for focal length adjustment. Since the manipulator precision alignment structure is based on the commercial high precision V-rail, a regular linear guiding system can be used for the focal length adjustment. Figure 8 shows two options of the linear guiding system for focal length adjustment.

To accommodate to the operation conditions on a diffractometer detector arm that may rotate in horizontal as well as vertical planes during diffraction studies, a micro-bearing has been added on the stage support structure as sown in Fig. 9 to confine the vertical tilting range of the flexural link subassembly. Figure 10 shows a 3D FEA model for the flexural link subassembly of the Y9-5101 CRL manipulator. The results showed that the maximum Von-Mises stresses on the 250 micron thick flexural link with various operation conditions are well below the material yield stress for 17-7-PH stainless steel.

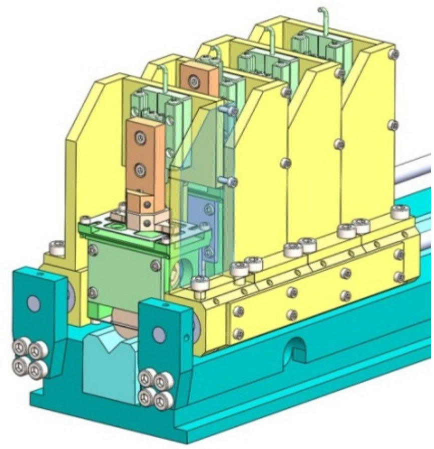

Figure 7: A 3-D model of a group of four Y9-5101 CRL manipulators mounted on a pair of linear guiding rails and linked together as a unit.

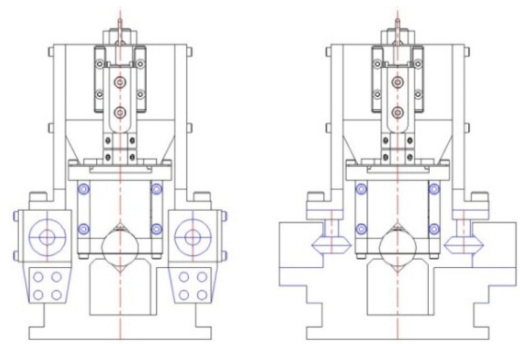

Figure 8: Schematic diagrams for the two options of the CRL manipulators linear guiding system for focal length adjustment. Left: using Thomson™ ball Bushing™ system [12]. Right: using THK™ V-rails and rolling wheels.

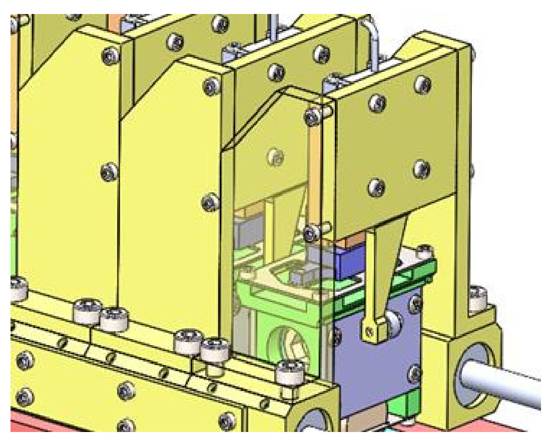

Figure 9: A 3-D model of the APS Y9-5101 compact manipulator with micro-bearing added on the stage support structure to confine the vertical tilting range of the flexural link subassembly.

ISBN: 978-3-95450-207-3 doi:10.18429/JACoW-MEDSI2018-WEOPMA04

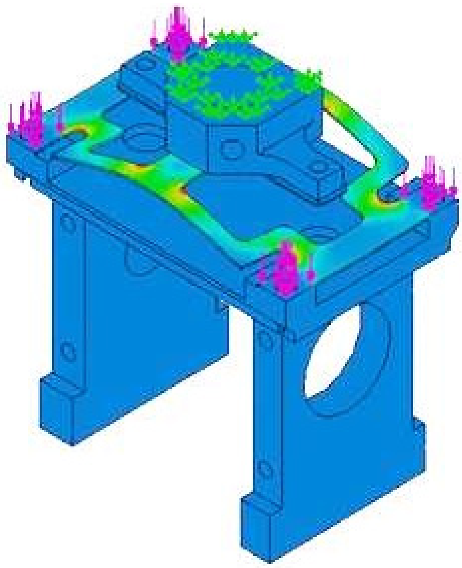

Figure 10: A 3-D FEA model for the flexural link subassembly of the Y9-5101 CRL manipulator.

DESIGN OF THE COMPACT MANIPULATOR FOR 32-MM CRL LENS STACK

To manipulate CRL lens stack with longer total length, a compact manipulator APS Y9-5102 for 32-mm CRL lens stack was designed using commercial piezo-driven linear actuator, such as Picomotor™ 8353 [13], as a lens manipulating driver with maximum axial driving force of 13 N. Figure 11 shows a 3D model of the Y9-5102 compact manipulator for 32-mm CRL lens stack.

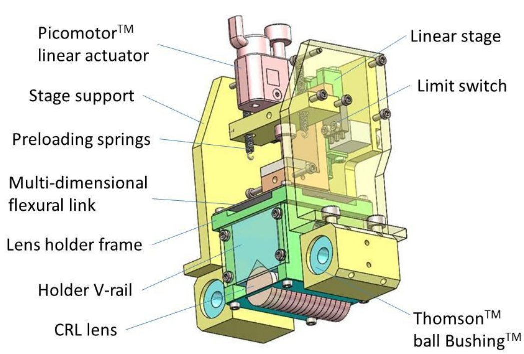

Figure 11: A 3-D model of the Y9-5102 compact manipulator for 32-mm CRL lens stack.

SUMMARY

The mechanical designs of a new precision alignment apparatus for compact x-ray CRL manipulator system are presented in this paper. This CRL manipulator system is specially designed for dark-field imaging of multi-scale structures at the APS. Comparing with existing CRL manipulator designs [14, 15], it is compact, and suitable to be implemented on a high-resolution diffractometer detector arm that rotates during diffraction studies with limited load capacity. A prototype for proof-of-principle has been built and tested at the APS with promising results.

Meanwhile, the compact modular designed CRL manipulators are compatible with high-vacuum (HV) or ultra-high-vacuum (UHV) operation conditions. The manipulators integration flexibility provides wide range of applications for synchrotron radiation instrumentation. Figure 12 shows a 3D model of a combination of four Y9-5101 and one Y9-5102 manipulators for a total of 48 CRL to be mounted on a Thomson™ rail system with 140-mm travel range for focal length adjustment on a high-resolution diffractometer detector arm for dark-field imaging application. Figure 13 shows a schematic diagram for a combination of four Y9-5101 and nine Y9-5102 manipulators for a total of 159 CRL with an overall manipulators dimension of 468-mm. The 1+2+4+8+16x9 CRL lenses arrangement provides the flexibility to select any number between 0 – 159 for the numbers of CRLs to be aligned into the x-ray beam.

ACKNOWLEDGMENT

The authors would like to acknowledge Patricia Fernandez and Dean Haeffner for their management support. Work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.

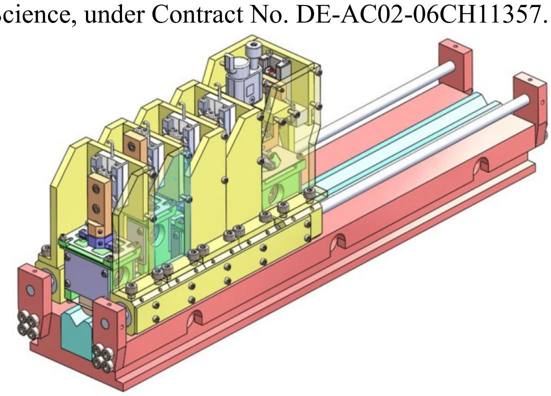

Figure 12: A 3-D model of a combination of four Y9-5101 and one Y9-5102 manipulators for a total of 48 CRL to be mounted on a Thomson™ rail system with 140-mm travel range for focal length adjustment. The motorized linear actuator for focal length adjustment is not shown in the figure.

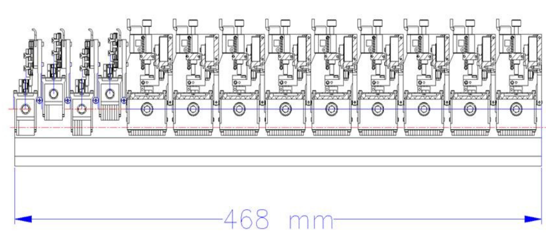

Figure 13: A schematic diagram for a combination of four Y9-5101 and nine Y9-5102 manipulators for a total of 159 CRL with an overall manipulators dimension of 468-mm.

ISBN: 978-3-95450-207-3 doi:10.18429/JACoW-MEDSI2018-WEOPMA04

REFERENCES

[1] H. Simons, A. King, W. Ludwig, C. Detlefs, W. Pantleon, S. Schmidt, F. Stöhr, I. Snigireva, A. Snigirev, and H. F. Poulsen, "Dark-field X-ray microscopy for multiscale structural characterization," *Nat. Comm.*, 6, Jan. 2015, paper 6098, DOI: 10.1038/ncomms7098.

[2] H. Simons, A. C. Jakobsen, S. R. Ahl, C. Detlefs, H.F. Poulsen, "Multiscale 3D characterization with dark-field x-ray microscopy," *MRS Bulletin*, 41, June 2016, pp. 454-459, DOI: 10.1557/mrs.2016.114.

[3] J. Hilhorst, F. Marschall, T. N. Tran Thi, A. Last, and T. U. Schülli, "Full-field X-ray diffraction microscopy using polymeric compound refractive lenses", *J. Appl. Cryst*., 47, 2014, pp. 1882-1888, DOI: 10.1107/S1600576714021256.

[4] W. Ludwig, P. Cloetens, J. Härtwig, J. Baruchel, B. Hamelin, and P. Bastie, "Three-dimensional imaging of crystal defects by 'topo-tomography'", *J. Appl. Cryst.*, 34, Oct. 2001, pp. 602-607, DOI: 10.1107/S002188980101086X.

[5] F. Marschall, A. Last, M. Simon, M. Kluge, V. Nazmov, H. Vogt, M. Ogurreck, I. Greving, and J. Mohr, "X-ray full field microscopy at 30 keV", *J. Phys. Conf. Ser.,* April 2014, DOI: 10.1088/1742-6596/499/1/012007.

[6] S. R. Ahl, H. Simons, A. C. Jakobsen, Y. B. Zhang, F. Stöhr, D. Juul Jensen, and H. F. Poulsen, "Dark field X-ray microscopy for studies of recrystallization", *IOP Conf. Ser.: Mat. Sci. Eng.*, vol. 89-1, 2015, DOI: 10.1088/1757-899X/89/1/012016.

[7] A. Snigirev, V. Kohn, I. Snigireva, B. Lengeler, "A compound refractive lens for focusing high-energy X-rays", *Nature*, vol. 384, iss. 6604, Nov. 1996, pp. 49-51, DOI: 10.1038/384049a0.

[8] B. Lengeler, C. Schroer, J. Tummler, B. Benner, M. Richwin, A. Snigirev, I. Snigireva, M. Drakopoulos, "Imaging by parabolic refractive lenses in the hard X-ray range", *J. Synchrotron Rad.*, vol. 6, 1999, pp. 1153-1167, DOI: 10.1107/S0909049599009747.

[9] RXOPTICS, http://www.rxoptics.de/intro.html.

[10] THK, http://www.thk.com.

[11] SmarAct, http://www.smaract.com.

[12] Thomsonlinear, https://www.thomsonlinear.com.

[13] Newport, https://www.newport.com.

[14] G. M. A. Duller, D. R. Hall, and A. Stallwood, "F-Switch: Novel 'Random Access' Manipulator for Large Numbers of Compound Refractive Lenses", in *Proc. MEDSI'16*, Barcelona, Spain, Sep. 2016, paper WEPE22, pp. 345-347, DOI: 10.18429/JACoW-MEDSI2016-WEPE22.

[15] JJ X-ray, https://jjxray.dk.