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Mechanical Design of Multiple Fresnel Zone Plates Precision Alignment Apparatus for Twenty-Nanometer Scale Hard X-ray Focusing

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Abstract - To overcome the limitations in today's fabrication techniques for high-efficiency Fresnel zone plates (FZPs) capable for hard x-ray focusing in the twenty-nanometer scale, a new approach of stacking FZPs in an intermediate-field was published by Vila-Comamala et al. in 2012 [1]. With this approach, a precision alignment apparatus for multiple FZPs handling and aligning must be designed to meet the following challenging design requirements: 1) Each of the stacking FZPs need to be manipulated in three dimensions with nanometer-scale resolution and travel range of several millimeters. 2) The relative three-dimensional stabilities between all of the stacking FZPs (especially in the x-ray beam transverse plane) are required to be kept within few nanometers for more than eight hours, the duration of the hard x-ray focusing for nanoprobe operation. 3) Compatible with the operation of multiple optics configurations for the Advanced Photon Source (APS) future x-ray nanoprobe design. Several prototypes have been designed and tested at the APS. In this paper we present the precision mechanical design of the apparatus prototypes for two, three, and six FZPs alignment in an intermediate-field, as well as the test results of their hard x-ray focusing performances.

***Keywords*:** Fresnel zone plate, multiple zone plate stacking, thermal stability, hard X-ray focusing

1. Introduction

As diffractive optics suitable for x-ray focusing, Fresnel-zone-plate (FZP) based optics is extensively applied for x-ray instruments [1]. Many synchrotron radiation beamlines are using FZPs for hard x-ray focusing at the APS at Argonne National Laboratory (ANL). Since focusing efficiency of FZPs for hard x-rays depends on zone height, while the achievable spatial resolution depends on the width of the outmost zone, very high aspect ratio structures are required for hard x-ray focusing with focal spot size of few tens of nanometers, which is required for future hard x-ray nanoprobe beamlines planned as part of the APS Upgrade project [2,3]. FZPs applied for such hard x-ray nanoprobe with optimal efficiency are difficult to be manufactured with current technology.

To overcome the limitations of today's fabrication techniques for high-efficiency hard x-ray FZPs, and to avoid the challenges of the proximity condition for near-field stacking of identical FZPs, in 2012, Vila-Comamala et al. proposed a new idea to stack FZPs in an intermediate-field with larger distances [4]. According to this new method, stacking zone plates with large separation distance is possible by adjusting the diameter of the downstream FZP so that its focal length is equal to the focal length of the upstream FZP minus the distance between both FZPs. Thus, the focal spots of both FZPs overlay when the separation of both FZPs matches the difference in focal lengths.

To transfer this new idea from theory to a practical instrument, besides designing and fabricating of high quality FZPs for intermediate-field stacking, there are many technical challenges to design a precision alignment apparatus for multiple FZPs handling and aligning. First of all, each of the stacking FZPs needs to be manipulated in three dimensions with nanometer-scale resolution and several millimeters travel range. Secondly, the relative three-dimensional stabilities between all of the stacking FZPs (especially in the x-ray beam transverse plane) are required to be kept within few nanometers for more than eight hours, the duration of the hard x-ray focusing for nanoprobe operation. Finally, the alignment apparatus should be compatible with the operation of multiple optics configurations for the Advanced Photon Source (APS) future x-ray nanoprobe design.

Several alignment apparatus prototypes have been designed and tested at the APS to prove the principle of FZPs stacking in an intermediate-field. The experiences gained from initial prototypes for two and three FZPs intermediate-field stacking confirmed that there is a need to develop a new design approach for precise thermal-mechanical displacement compensation in nanometer scale. The alignment apparatus Z2-37 for three, six or more FZPs stacking was developed with the new design. In this paper we present the design of these apparatus prototypes, as well as the test results of their hard x-ray focusing performances.

2. Alignment apparatus prototypes for two and three Fresnel zone plates stacking

2.1. Apparatus Z2-33 for two FZPs stacking

The prototype of alignment apparatus Z2-33 is designed for two FZPs stacking to enable the first experiment of stacking FZPs with adjusted diameter in the intermediate field. As shown in Figure 1, a pair of commercial Piezo-motor-driven linear stages (SmarActTM SLC-1720S) are mounted on the zone plate alignment base to provide 2-D alignment for the upstream zone plate in X-Y plane. To adjust the distance between the upstream and downstream zone plates, the downstream zone plate holder is driven by a SmarActTM SLC-1720S linear stage in Z-direction. All of the three piezo linear positioners are mounted on a zone plate alignment base frame, which is a part of the carriage of a 2D-tilting stage. The V-axis tilting stage is driven by a picomotor^{TM} actuator, and rotates around a vertical pin, which is fixed on the base of the 2D-tilting stage and sliding fitted with the base of the H-axis stage. The H-axis stage tilts around a pair of flexural pivot.

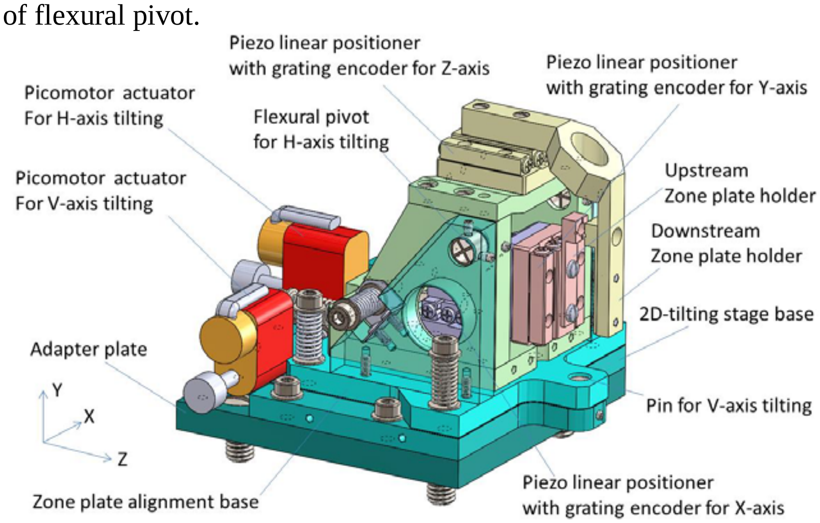


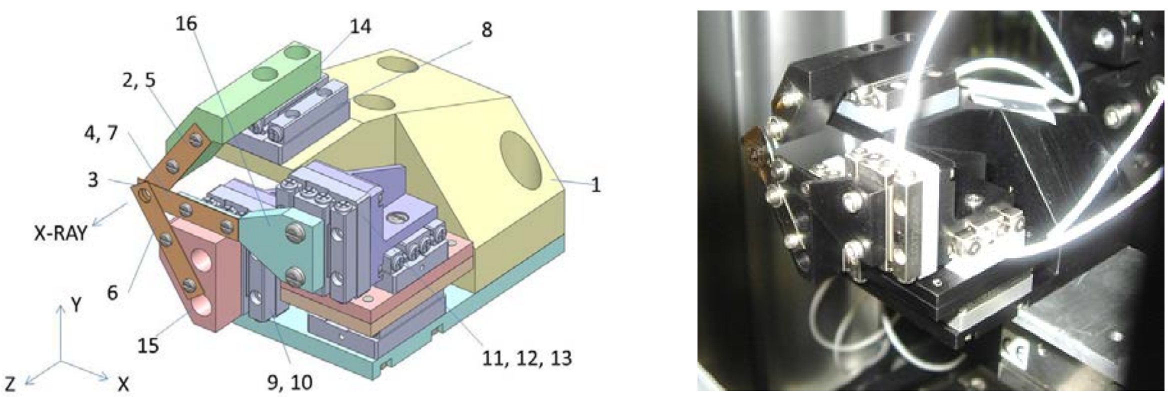
Figure 1. A 3-D model of a prototype of Z2-33 alignment apparatus for two FZPs stacking.

Using alignment apparatus Z2-33, the simulations by Vila-Comamala et al. for two FZPs stacking in the intermediate field have been proven experimentally at the APS.

2.2. Apparatus Z2-34 for two FZPs stacking

The prototype Z2-34 is an alignment apparatus for three FZPs stacking with non-symmetric configuration [5,6]. It is compatible with mirror-based nanofocusing optics, such as Kirkpatrick-Baez (K-B) mirrors [7] for hard x-ray nanoprobe in switchable multi-optics operation modes. Figure 2a shows a 3-D model of the prototype of alignment apparatus Z2-34. It has a non-symmetric invar base structure (1) and six commercial Piezo-motor-driven linear stages (SmarAct^{TM} SLC-1720S). There are three FZPs (2-4) mounted on FZP holders (5-7). Since the thermal expansion coefficient of CVD diamond is similar to the thermal expansion coefficient of invar, the FZP holders for Z2-34 were made from CVD diamond blades. The CVD-diamond holder (5) for upstream zone plate (2) is driven by a stage (8) to adjust its position in the Z direction with nanometer scale and stability. The second downstream zone plate (3) is driven by a pair of stages (9,10) to adjust its position in the X and Y directions. The third downstream zone plate (4) is driven by a set of stages (11-13) to adjust its position in the X, Y, and Z directions.

Figure 2b shows a photograph of the Z2-34 alignment apparatus for three FZPs stacking test at the APS 2-ID-E hard x-ray experiment station. With the Z2-34 apparatus, measurements were performed under two different incident energies, 10 keV and 11.8 keV to address the energy dependence of efficiency and optimum structure thickness. The influences of lateral and longitudinal misalignment were also measured and compared with computer-aided theoretical simulations [5].



(a) *(b)*

Figure 2. (a) A 3-D model of the prototype of alignment apparatus Z2-34 with non-symmetric configuration. (b) A photograph of the Z2-34 alignment apparatus for three FZPs stacking test at the APS 2-ID-E hard x-ray experiment station.

3. Design approach for thermal-mechanical displacement compensation in nanometer scale

Both finite element analyses (FEA) and experimental results gained from the Z2-34 prototype showed that due to Z2-34's non-symmetric structure and the materials applied for SmarAct^{TM} SLC-1720S stage's base (aluminum alloy) and linear bearings (stainless steel), the zone plate's thermal drifting in lateral directions is in the range of 100 - 200 nm for one degree of temperature variation, even though the Z2-34 is built with invar base and CVD diamond FZP holders. For FZPs with 100-nm-scale hard x-ray focusing in a typical APS experimental station environment with +/- 0.1 degree of temperature variation, the Z2-34 alignment apparatus barely meets the thermal-mechanical stability requirement. To optimize the FZPs alignment apparatus for 20-nm-scale hard x-ray focusing, expensive customized stages with invar linear bearings and invar stage base may be required. Otherwise, a new design approach for precise thermal-mechanical displacement compensation in nanometer scale should be developed.

Figure 3 shows a 3-D model of the new design approach for the X-Y-Z stage sub-assembly module Z2-3701 with CVD diamond holder and linkage component [6]. With this new modular design, each of the zone plate CVD-diamond holders is driven by a set of stages to adjust its position in the X, Y, and Z directions. Similar to the zone plate holders for Z2-34 alignment apparatus, the zone plate holders for Z2-3701 alignment apparatus are made of CVD diamond material to ensure thermal stability of the apparatus. Materials of the linkage components between the stages and CVD-diamond holders are also carefully chosen to further compensate the thermal deformation from the stage set. Thermal expansion between FZP mounting position and Z2-3701 mounting base could be compensated by the following effects:

- Different materials for adapters G and H;
- Different materials for holder parts J and K;
- Different bonding location for holder parts J and K;
- Mounting position and force on control points A, B, C, D, E, and F;
- X-Y-Z Stage positions.

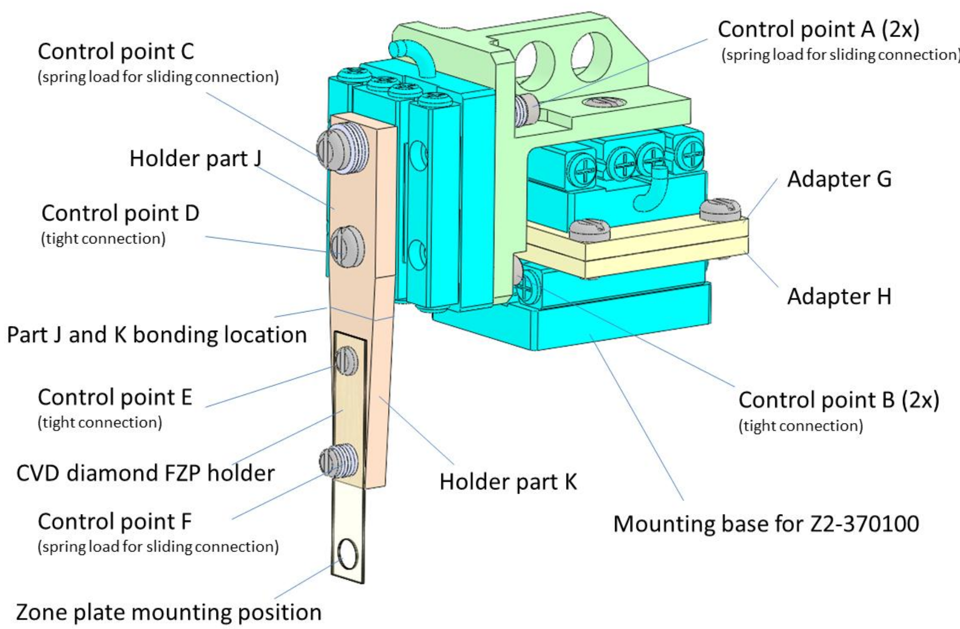


Figure 3. A 3-D model of the Z2-3701 X-Y-Z stages sub-assembly module with CVD diamond holder and linkage component.

As an example, Figure 4 shows a 3-D FEA model of the Z2-3701 X-Y-Z stages sub-assembly module for thermal drifting in Y direction under a 1 ^{o}C temperature variation at y-stage neutral position. Table 1 shows the FEA results for zone plate thermal drifting in the Y direction under 1 ^{o}C temperature variation with different Y-stage positions. In this study, the linkage material is SS304 and the adapters material is AL6061. The results show that, with the Z7-3701 module, it is feasible to design a multiple FZP alignment apparatus with a better than 2 nm thermal-mechanical stability in an experiment environment with +/- 0.1 degree of temperature variation. More detailed FEA results are presented in a separate MEDSI-2014 paper [8].

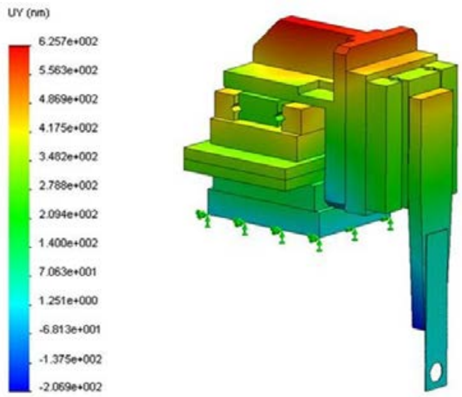


Table 1. FEA results for zone plate thermal drifting in the Y direction under 1 °C temperature variation with different Y-stage positions.

Y-Stage Position (mm)	Y (nm)
1.0	-6.5
0	-2.3
-0.5	-0.61
-0.6	-0.61
-0.7	-0.17
-0.75	0.061
-0.8	0.24
-1.0	1.4

Figure 4. A 3-D model of the Z2-3701 X-Y-Z stages sub-assembly module for thermal drifting in Y direction under a 1 °C temperature variation at y-stage neutral position. In this study, the linkage material is SS304 and the adapter material is AL6061.

4. Alignment apparatus Z2-37 for three, six or more Fresnel zone plates stacking

Based on the design of the Z2-3701 X-Y-Z stages sub-assembly module, we have designed, constructed, and tested the Z2-37 precision alignment apparatus for six zone plates intermediate-field stacking as shown in Figure 5 [6]. The Z2-37 alignment apparatus has a hexagon symmetric invar base structure (1) with an interface mounting plate (38) and up to eighteen commercial Piezo-motor-driven linear stages (such as SmarAct™ SLC-1720S, PITM LPS-24, or Micronix™ PPS-20 stages). Six zone plates (2-7) are mounted on CVD-diamond holders (8-13). It is especially useful for hard x-ray focusing with x-ray energy 25 keV and above.

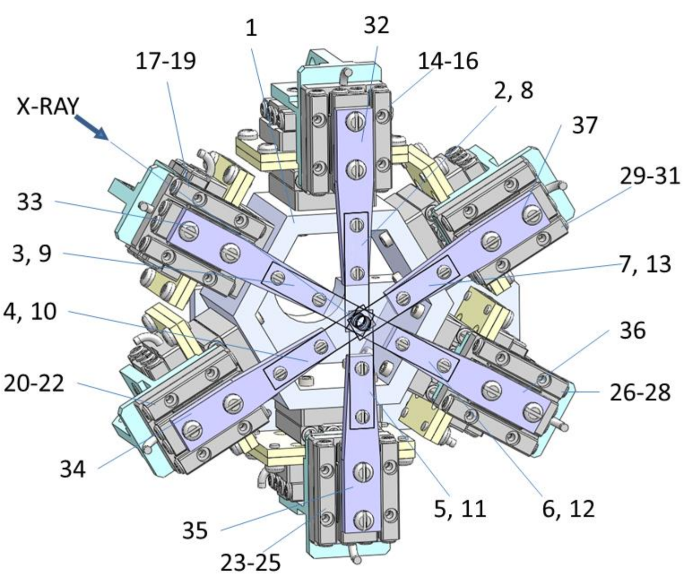
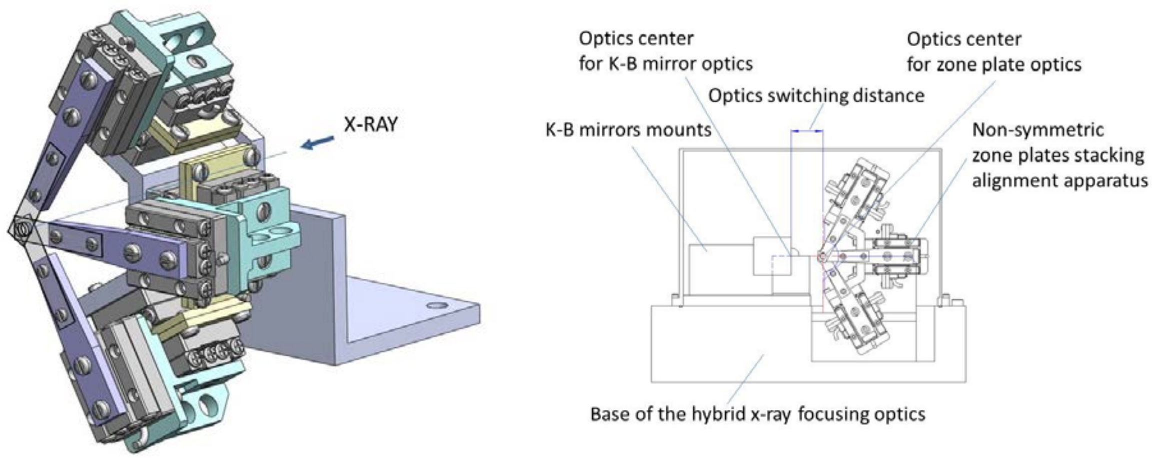


Figure 5. A 3-D model of the Z2-37 precision alignment apparatus for six zone plates intermediate-field stacking: (1) invar base structure; (2-7) zone plates; (8-13) CVD-diamond holders; (14-31) X-Y-Z stages; (32-37) linkage components; (38) an interface mounting plate.

Similar design with an octagon or decagon symmetric invar base structure and twenty-four or thirty commercial Piezo-motor-driven linear stages can perform eight or ten FZPs intermediate-field stacking for high energy x-ray focusing applications.

With a non-symmetric invar base structure and three Z2-3701 X-Y-Z stages sub-assembly modules, prototype Z7-3709 is designed for three FZPs stacking compatible with mirror-based nanofocusing optics, such as Kirkpatrick-Baez (K-B) mirrors for hard x-ray nanoprobe in switchable multi-optics operation modes as shown in Figure 6 [6]. The hybrid hard x-ray focusing optics has a minimized horizontal switching distance (< 16 mm). In this configuration, the zone plate optics and K-B mirror optics will share a high-stiffness flexure-based 2D-tilting stage through the base of the hybrid x-ray focusing optics.



(a) (b)

Figure 6. (a) A 3-D model of the Z2-3709 precision alignment apparatus for three FZPs intermediate-field stacking with non-symmetric invar base structure and three Z2-3701 X-Y-Z stage sub-assembly module. (b) Schematic diagram of the hybrid hard x-ray focusing optics with K-B mirror optics and zone plate optics using Z7-3709 non-symmetric precision alignment apparatus for three FZP intermediate-field stacking.

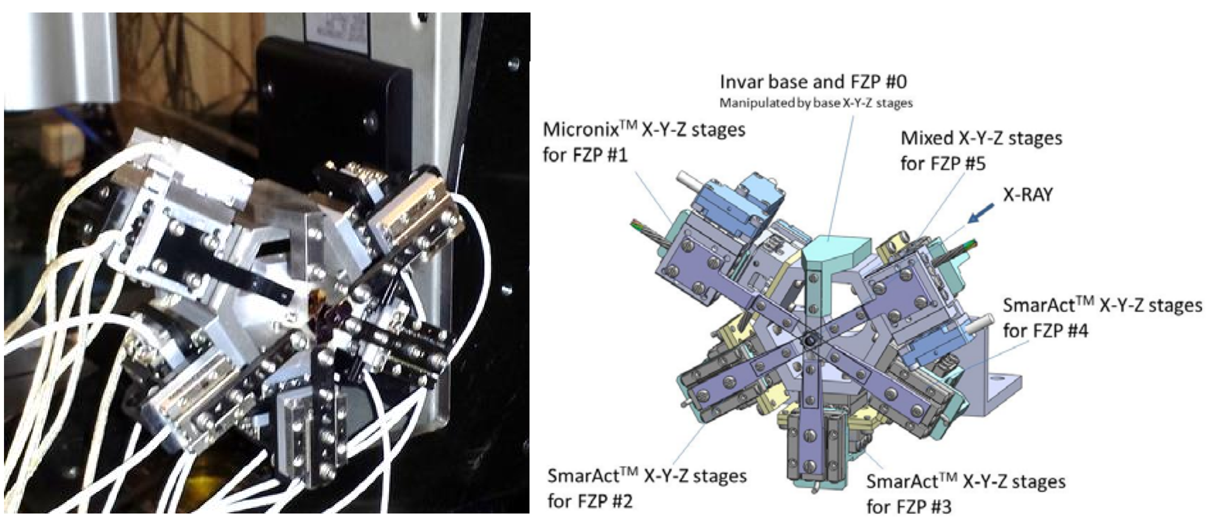
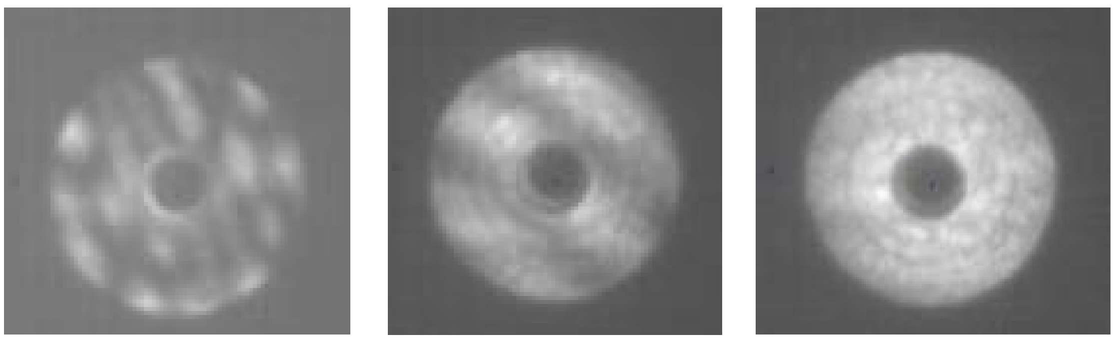


Figure 7. (a) A photograph of the Z2-37 alignment apparatus prototype for five FZP intermediate-field stacking test at the APS 2-ID-D hard x-ray experiment station. (b) A 3-D model of the Z2-37 alignment apparatus prototype for the APS 2-ID-D first test with five FZP intermediate-field stacking.

5. Preliminary test for five FZPs stacking

Using the Z2-37 stacking alignment apparatus as shown in Figure 7, a test for stacking five zone plates with 80 nm outmost zone width was performed at the APS undulator beamline experimental station 2-ID-D at 25 keV. The preliminary test showed an 8-fold increase of efficiency compared with a single zone plate at 25 keV. Figure 8 shows Moire fringes on the scintillator crystal created before final tweaking for the five FZPs alignment. The initial successful x-ray tests demonstrated the positioning and stability performance of the stacking alignment apparatus. First user operation using Z2-37 alignment apparatus at the APS 2-ID-D station with 22.5 keV and 200 nm – 300 nm x-ray focal spot started on July 8, 2014. Detailed x-ray test results will be published in separated papers [5,9].



(a) (b) (c)

Figure 8. Moire fringes on the scintillator crystal created before final tweaking for the five FZPs alignment at APS 2-ID-D. (a) July 8, 2014, 08:06 am, Moire fringes after 4 days APS machine studies. (b) Moire fringes at 08:35 am, July 8, 2014. (c) User operation started at 09:08 am, July 8, 2014.

6. Summary

The mechanical design of multiple FZPs precision stacking alignment apparatus for the hard x-ray focusing is presented in this paper. FEA results and initial x-ray experimental measurements have shown that the mechanical design of the Z2-37 precision alignment apparatus system is capable to meet design requirements for the hard x-ray focusing in the twenty-nanometer scale. We have successfully demonstrated stacking of three and five zone plates in the intermediate field [5,9].

Thanks to the large travel range and good positioning repeatability of the alignment stages, the Z2-37 apparatus enables working with arrays of FZPs, dedicated FZPs could provide the possibility to switch FZPs to select optimum resolution for varying focus spot size requirements and a wide range of incident energy [5]. Further x-ray tests for six or more zone plates with 20 nm outmost zone width for higher spatial resolution are in progress.

Acknowledgements

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