Statement of Work

Dynamic Compression Sector
KB Mirror System
Statement of Work

DCS Point of Contact (POC): Paulo Rigg
Responsible Institution: Argonne National Laboratory
Responsible Institution POC: Yuelin Li
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Abstract – This document describes the technical specifications and requirements to design and manufacture a KB focusing mirror system for the Dynamic Compression Sector, 35-ID at the advanced Photon Source.

Table of Contents

1 Scope Description

1.1 Background

The Advanced Photon Source Upgrade Project (APS-U) is planning a storage-ring upgrade that will reduce the electron-beam emittance by a factor of ~75. This ultra-low emittance is achieved by replacing the present storage ring lattice with a multi-bend achromat (MBA) lattice. The MBA lattice will increase the coherent x-ray fraction by two orders of magnitude and decrease the horizontal source size by a factor of ~20.

To take full advantage of these exciting new x-ray source properties, optics to focus the beam to a smaller beam size (30-100 micron or smaller depending on the experiment hutch) are necessary. The Dynamic Compression Sector (DCS) beamline at 35-ID, operated by Washington State University (WSU) and developed jointly by the Advanced Photon Source (APS) with funding from the U.S. Department of Energy National Nuclear Security Administration, is a first-of-its-kind capability dedicated to dynamic compression science. We plan to modify the DCS beamline to cover an energy range of up to 70 keV during the construction of APS-U.

Currently, a water-cooled Kirkpatrick-Baez (KB) mirror system is installed and operating at a 2.1 mrad incidence angle. The system serves as a horizontal and vertical focusing element and provides rejection of higher harmonics. The Horizontal Focusing Mirror (AHFM) is located at 35.6 m and the Vertical Focusing Mirror (AVFM) at 37.1 m from the x-ray source. The mirror system covers 7-36 keV x-ray energies, which is limited by the 2.1 mrad operation angle and the platinum surface coating. A new mirror system, operating at a minimum incidence angle of 1 mrad, is required to extend the x-ray energy to 70 keV. To enhance the high harmonic rejection capability, we also require the highest pitch to be at 2.7 mrad.

This SOW describes requirements for a Kirkpatrick-Baez mirror system (35-ID-KB-Mirror) to be installed at the Sector 35 insertion device beamline. This system is designed based on the mirror location at 35 ID-A hutch that will provide a full-beam focusing and with a focused beam size around 20 μm at photon energy ranging from 7 keV to 70 keV.

This document is a request for a proposal that specifies the design, manufacture, test, delivery, and installation of the mirror system. The overall lifetime of the system should be more than ten years.

Please provide separate proposals for the following systems with the specifications described in this document:

- One proposal for a system consisting of only the vertical KB mirror. This new vertical mirror will be used in conjunction with the existing horizontal mirror.
- One proposal for a system consisting of both horizontal and vertical KB mirrors to replace both existing mirrors. Such a system may consist of a single

vacuum chamber that contains both mirrors or separate vacuum chambers for each mirror.

1.2 Scope Details

A full system contains:

- The 35-ID-KB-Mirror(s) with optical coating, mirror mounting, bending mechanism, and cooling system, protective mask, feedthroughs, alignment motions, travel motions, and travel limits.
- Ion pump, cables, vacuum readout and controller.
- Vacuum chambers, windows, and vibration suppressed supporting structure with alignment mechanism if needed.

1.3 Beamline Description

Schematics of the current DCS, or APS 35-ID beamline, layout are shown in Figure 1. After the APS Upgrade, the 35-ID beamline will operate over an energy range of 7 to 70 keV. The DCS performs single shot diffraction, imaging, and spectroscopy experiments. To maximize single pulse photon flux, the source for the beamline will be two revolver insertion devices in tandem producing a single x-ray beam. The front end will incorporate a novel beam position monitor and include the APS standard radiation safety equipment with all required shielding and aperture systems to reduce Bremsstrahlung and the total radiation power.

35-ID Beamline has five experimental stations, successively labeled as 35-ID-A, 35-ID-B, 35-ID-C, 35-ID-D, and 35-ID-E, as shown in Figure 1, 35-ID-A will house the mirror system described in this SOW which will replace the existing mirror system if the two-mirror system is chosen or replace the AVFM only if the one-mirror system is chosen. Configuration changes to the existing A Station components will be made to accommodate the new mirror system.

Dec. 9, 2022

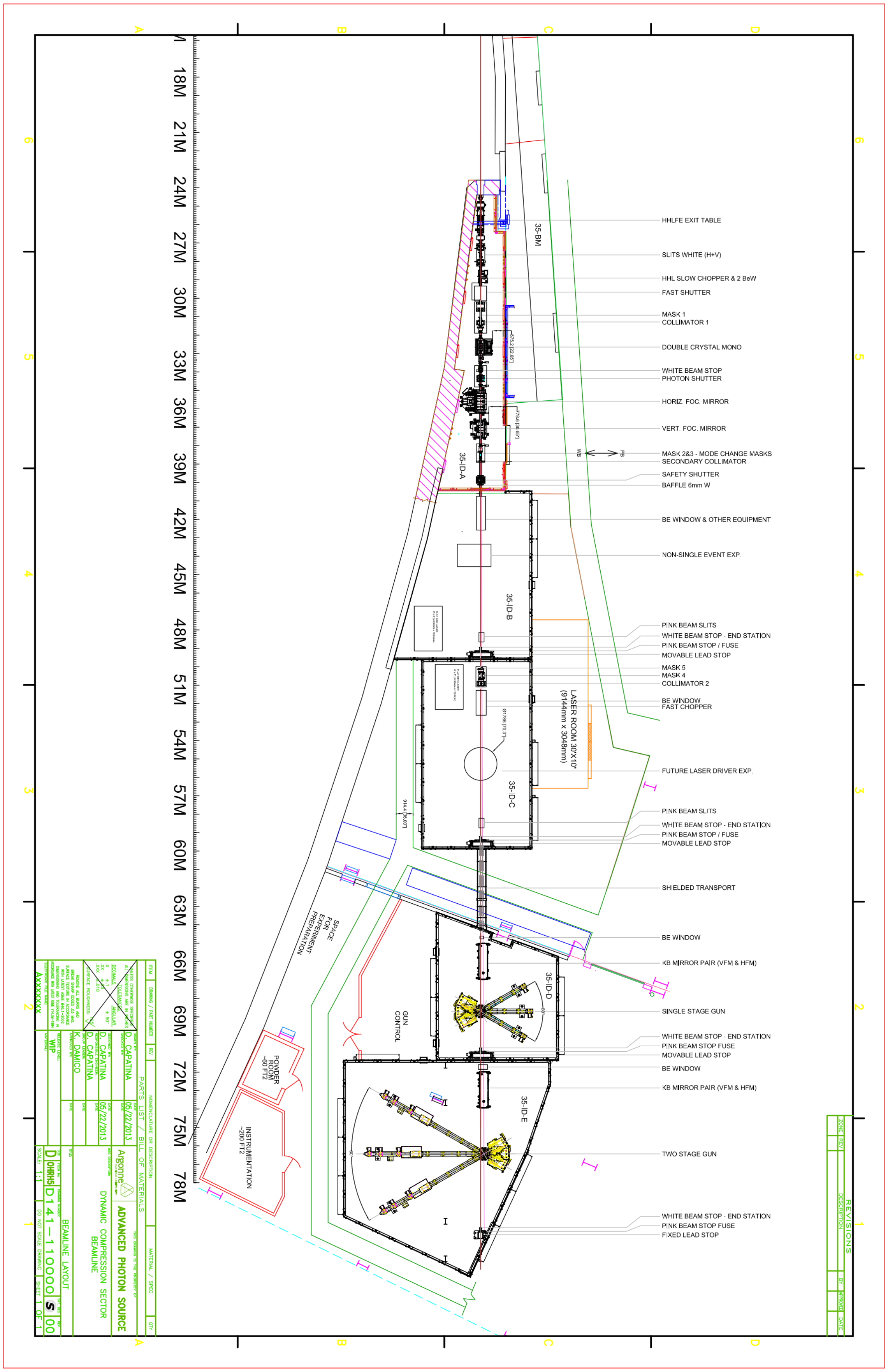

Figure 1a: Floor plan and optics layout for beamline 35-ID.

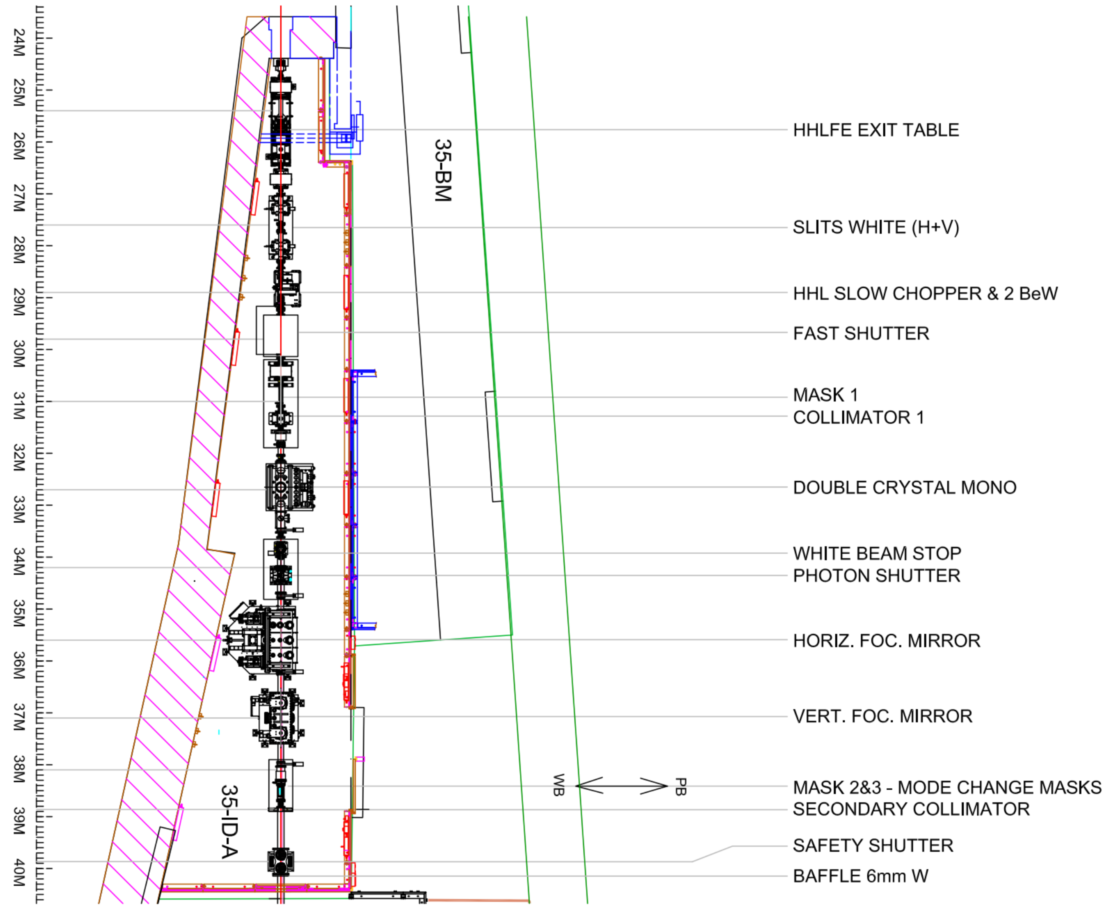

Figure 1b: Current layout of station 35-ID-A.

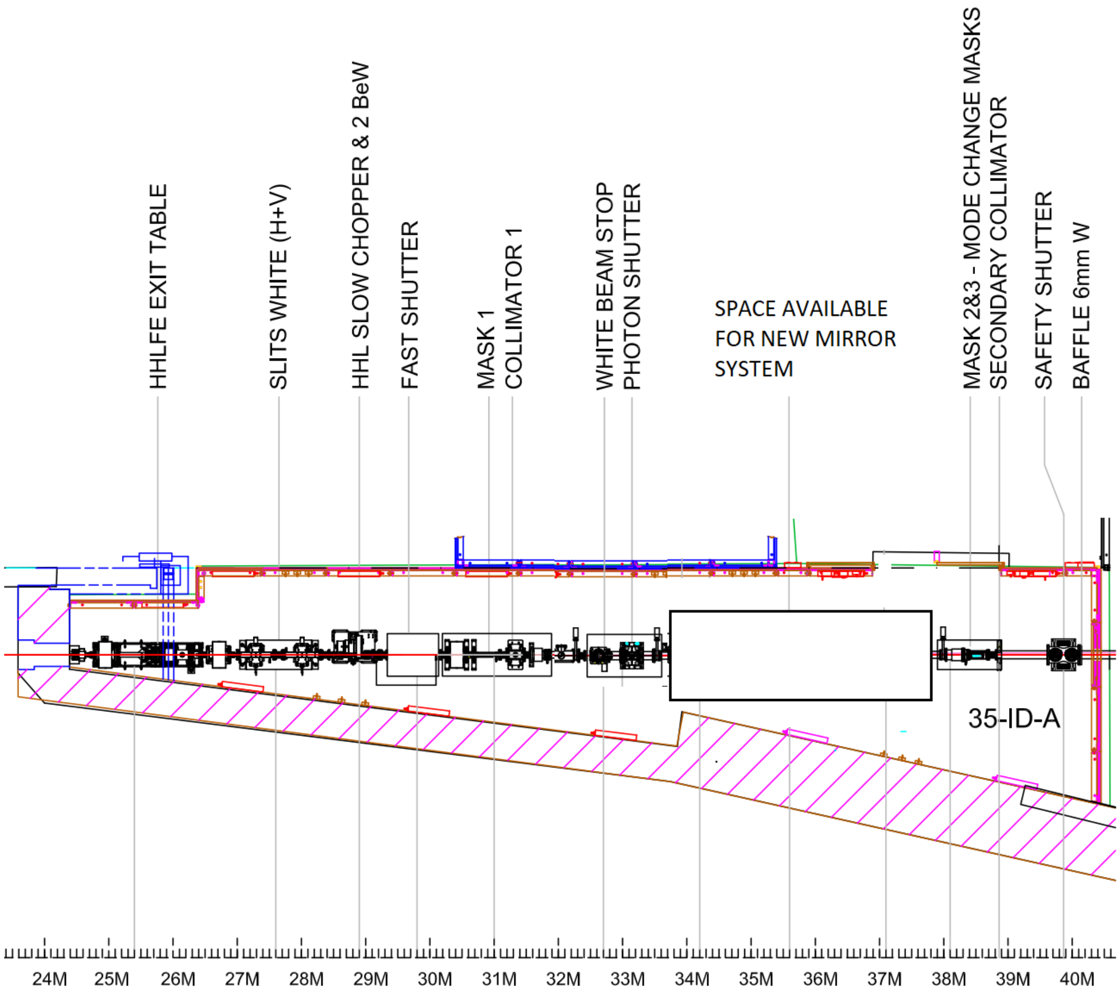

Figure 1c: Layout for the new K-B mirror system location in 35-ID-A station.

1.4 Schedule

Table 1.4.1 Proposed Schedule Table

Item	Description	Weeks for Item	Total Weeks ARO*
Contract Award	Project Start	0	0
Initial Project Meeting	Provide project schedule	1	1
Preliminary Design Report (PDR)	Document to be provided to APS for review	4	5
APS Review	Review of PDR/Approval to Proceed	1	6
Final Design Report (FDR)	Document to be provided to APS for review	5	11
APS Review	Review of FDR/Approval to Proceed	1	12
Fabrication of mechanical systems and mirror substrate	Period when device is being fabricated.	40	52
Integration of substrate and mechanical systems	Assembly and testing at vendor facility	4	56
Ship to APS	Item in transit to APS	2	58
Metrology testing at APS; Installation	Vendor unpacking, assembly, installation	2	60
Final acceptance/closeout	All documentation provided	0	60

*After Receipt of Order

There are 7 major milestones:

1. Initial Project Meeting
2. Preliminary Design Review
3. Final Design Review
4. Brief Monthly Manufacturing Progress Reports
5. Shipping of device from the vendor to the APS
6. Installation at the APS
7. Final Project Closeout

The vendor shall propose a schedule such that all items will be shipped to APS not more than 60 weeks after receipt of order.

1.5 Reports and Documentation

The following documents and reports are to be provided at the following stages:

1.5.1 Initial Project Meeting

- A schedule consistent with the above milestones and schedule

1.5.2 Preliminary Design Review

- Preliminary Design Report (30-60% design completion)

- Drawings with sufficient detail to support the device being specified at preliminary level
- Description of all motion controls components
- Manufacturing drawings in PDF format
- 3D models in STEP format
- 2D assembly drawings in DWG or DXF format

1.5.3 Final Design Review

- Final Design Report (including the following)
- Drawings sufficient to support the device being nearly completely designed
- Manufacturing drawings in PDF format
- 3D models in STEP format
- 2D assembly drawings in DWG or DXF format
- Electrical drawings in PDF format with schematics of all motor, encoder, piezo, and sensor wiring and connection panels
- Finalize coupling support-structure coupling-mechanism design
- Factory acceptance test procedures and schedule
- Vendor acceptance test procedures at APS Site

1.5.4 Monthly Progress Reports

- Brief monthly progress reports will be submitted to APS. These reports may be a bulleted list in an email that details the manufacturing progress

1.5.5 Shipping

- Shipping and packaging plan one month prior to shipping
- Factory acceptance test sent to and approved by APS before shipping
- The vendor should prepare an *Interface Requirements Document* that describes the vendor's technical support needs and infrastructure requirements during installation at the APS. (e.g. APS Survey Group, ANL Riggers, portable clean room, etc…). These should be sent to the APS one month before shipping.
- Schedule for APS installation activities

1.5.6 Contract Closeout

- As-built drawings
- Manufacturing drawings in PDF format
- 3D models in STEP format
- 2D assembly drawings in DWG or DXF format
- Factory acceptance test procedures and report
- User's manuals and procedures for system operation, maintenance, assembly, disassembly, storage, and on-site installation
- Manuals and warranties for all 3rd party components
- Manuals for precision motion components, if applicable
- APS site acceptance test procedures and report

- Quality Assurance Documents for the completed systems, including a list of used materials with their description, copies of material certificates, details of all quality control checks, and intermediate test results, as specified in the accompanying Quality Assurance Procurement Requirements Form ANL-407

1.6 Warranty

The 35-ID-KB-Mirror system shall be warranted for 12 months after final acceptance at APS or 15 months from delivery, whichever comes first. If delivery occurs before the APS-U construction project is completed (expected Apr 2024) then the start of the warranty shall be after the construction of APS-U is completed, thereby extending the warranty end dates.

2 Functional Description

2.1 Design Concept

The 35-ID-KB-Mirror system shall consist of two mirrors which focus the x-ray beam vertically and horizontally independently. As described above, this system will either utilize a new VFM in conjunction with the existing HFM or a system utilizing both a new VFM and HFM to replace the existing mirrors. In order to minimize the photon loss during focusing, the mirror(s) shall have a large angular acceptance to accept the full beam (4σ widths, >95% of intensity being collected). The mirror(s) shall have three different stripes for the reflecting surfaces – bare silicon substrate, rhodium, and platinum – to cover photon energies from 7 to 70 keV.

The center of the first mirror (35-ID-KB-HFM) will be located at about 34-35 m (exact location TBD) from the center of the straight section. It is supported from the inboard side and shall deflect in the outboard direction (away from the storage ring) through an angle between 2.0 to 5.4 milliradians (1.0-2.7 mrad incident angle) for x-rays from 7 keV up to 70 keV. *Note that if the single-mirror system is chosen, the existing HFM will be relocated to this position within the A station.* The center of the second mirror (35-ID-KB-VFM) will be located at 36-37 m (exact location TBD) from the source and shall deflect the beam upward through an angle between 2.0 to 5.4 milliradians (1.0-2.7 mrad grazing incident angle) for X-rays from 7 keV up to 70 keV.

Each mirror requires three motorized motions, in X, Y, and a rotation around the Sagittal direction (pitch rotation, as described in Figure 2). The X and Y motion is to center the x-ray beam on the mirror and to select one of the three stripes as the reflecting surface, and the pitch rotation is to adjust the incident/deflection angle. For the pitch rotation, the axis of rotation shall be on the optical surface centered along the length of mirror. The pitch rotation shall include a PZT based actuator for fine-tuning and for potential beam stabilization control. In addition, angular adjustment in roll and yaw (both motorized) shall be provided for alignment purposes. All the motions of each mirror shall be completely independent of each other. The main focal point ranges from 46.0 m (front end of B hutch) to 76.3 m (target position of E hutch). To achieve the best focusing sizes possible, a proper bending mechanism is needed.

The mirror(s) shall be contained in a high-vacuum chamber. For the two-mirror system being requested, the mirrors may be contained in a single vacuum chamber or separate vacuum chambers according to best design practices. The vacuum chamber(s) shall be connected to the 35-ID-A beam entrance port to minimize photon losses.

2.2 APS Coordinate System

A universally used coordinate system for APS beamlines is shown in Figure 2a. The positive Z direction points along the beam direction. The positive Y direction is a vertical axis pointing upward. The positive X direction is pointing outboard, away from the APS storage ring. θ_X, θ_Y, and θ_Z are the rotations about X, Y, and Z axis, respectively. Based on this coordinate system, the motion of the 35-ID-KB-Mirror is defined in Figures 2b and 2c for horizontal and vertical mirrors, respectively. The Pitch rotation, Yaw rotation, and Roll rotation are defined for these two mirrors.

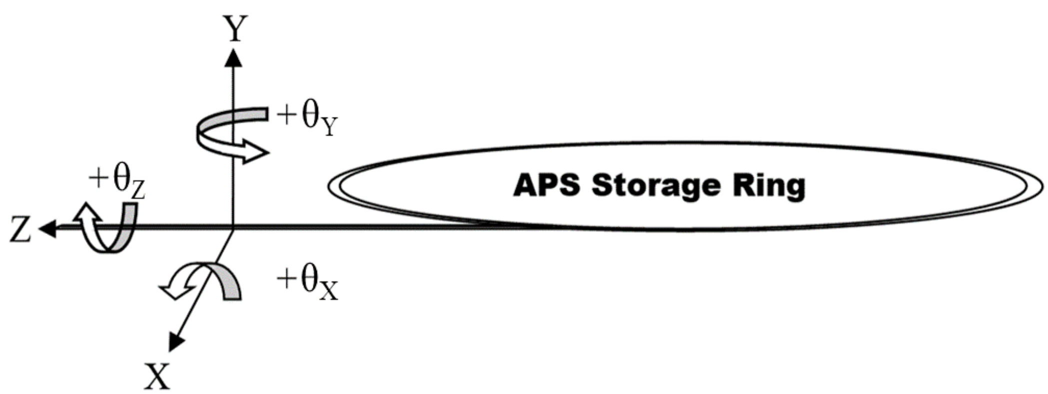

Figure 2a The APS coordinate system used at APS beamline and also in this document.

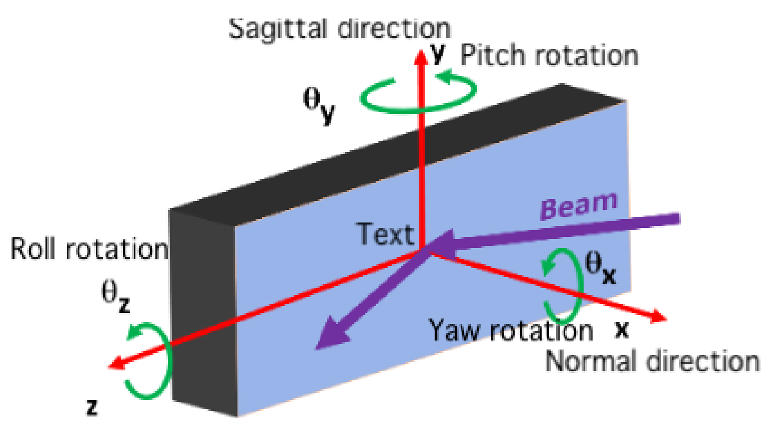

Figure 2b Schematic showing the coordinates of motion for the outboard deflecting horizontal mirror 35-ID-KB-HFM. Normal and Sagittal directions as well as the Pitch, Yaw and Roll rotations are defined relatively to the mirror surface.

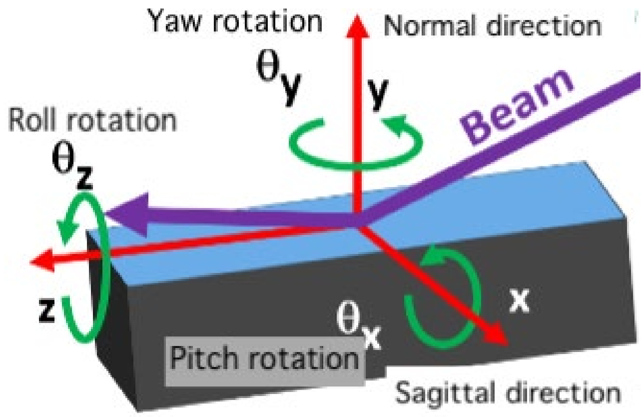

Figure 2c Schematic showing the coordinates of motion for vertically upward deflecting mirror 35-ID-KB-VFM. Normal and Sagittal directions as well as the Pitch, Yaw and Roll rotations are defined relatively to the mirror surface.

2.3 Translation in the Normal Direction of the Mirror

For translation along the mirror normal direction, requirements for the two mirrors are different. A motorized motion of +10 mm to -10 mm translation for 35-ID-KB-VFM and 35-ID-KB-HFM is required.

2.4 Translation in the Sagittal Direction of the Mirror

Overall motorized motions of ±35 mm (for 3 strips, 20mm each strip, plus 5 mm on each side) of the translation in the Sagittal direction for both mirrors are required to select one of the stripes as the reflecting surface.

2.5 Pitch Rotation about the Sagittal Direction

Minimum overall motorized motions range of -0.002/+0.005 radians of the Pitch rotation, a rotation about the Sagittal direction of each mirror is required to select the incident and deflection angles of the mirror. For this motion, the axis of rotation shall be on the optical surface centered along the length of the mirror. This motion needs to include a fine-scale piezo-driven (PZT) motion so that feedback control can be used to actively maintain the beam position. The required motion can be achieved through a combination of stepper and piezo-driven motors. The fine-tuning angular resolution is around 100 nano rad by the PZT.

2.6 Yaw Rotation about the Normal Direction

Overall motorized motions of ±0.05 radians of the Yaw rotation about the Normal direction for each mirror are required for alignment of the system.

2.7 Roll Rotation about the Z direction

Overall motorized motions of ±0.01 radians rotation of θ_Z Roll rotation of the horizontal and vertical mirrors are required for alignment of the mirror.

2.8 Twist angle adjustment (optional)

Motorized motions of twist angle adjustment for the horizontal and vertical mirrors are optional. This motion is required if the twist angle specification in Table 3.1.1 cannot be satisfied for the entire bending range.

2.9 Adjustable Hard Limits

Each motion of each mirror must be equipped with adjustable hard limits to restrict the range of motor motion once the mirrors have been aligned.

3 Specifications

3.1 35-ID-KB-Mirror specifications

Table 3.1.1

Parameters	Value	
	35-ID-HFM	35-ID-VFM
Mirror type	Flat, Bendable	Flat, Bendable
Mirror deflection orientation	Horizontal	Vertical
Nominal angle of incidence (milliradians)	1.0-2.7	1.0-2.7
Typical length of beam footprint in beam direction (mm) with 1.00 mm x 1.00 mm slits	1000	1000
Mirror		
Optical Surface size (mm)	1000x60	1000x60
Mirror Material	Si, single crystal	Si, single crystal
Stripes	Rh, Si, Pt	Rh, Si, Pt
Stripe configuration	Each stripe should be 20 mm wide and extend the entire length of the mirror along the beam direction. Typical Coating Thickness Specifications: Pt/Rh 250Å±10% over a Cr binding layer 100Å±20% The stripe material density should be > 95% bulk density. A witness substrate shall be coated along with the stripes and returned to the APS-U for characterization and approval before the mirror is shipped from the supplier.	
Non-optical ground surface finish (mm)	0.025	0.025
Optical Surface		
Tangential radius [km]	Flat, R > 300	Flat, R > 300
Sagittal radius [km]	Flat, R > 20	Flat, R > 20
Tangential RMS slope error (frequency 1/L~0.5 mm^{-1}) (µrad)	Separate quotations for ≤0.20 and ≤0.30	Separate quotations for ≤0.20 and ≤0.30
Tangential RMS height error (nm)	Separate quotations for <3.0 and ≤4.5	Separate quotations for <3.0 and ≤4.5
Sagittal RMS slope error (frequency 1/W~0.5 mm^{-1}) (µrad)	<5.0	<5.0
RMS micro-roughness after coating (Å)	<1.5	<1.5
Surface Quality	0.5 scratches or points (>Scratch Dig 10-5) per cm^2 over 99% of active optical area	
Mirror bender		
Minimum bending radius [km]	4.0	4.0
Bender added slope error [nrad]	<100 RMS	<100 RMS
Tangential surface figure	elliptical	elliptical
Twist angle*	<100 µrad	<100 µrad

*Defined as the angle between the upstream end edge and the downstream end edge, see Section 3.9 for details about the twist angle adjustment.

Table 3.1.2 Thermal Parameters

Parameters	Value***	
Thermal and vacuum Management	35-ID-HFM	35-ID-VFM
Maximum absorbed power under nominal operation (W)*	400/55	10/14
Peak power density on the mirror surface under nominal operation (W/mm^2)*	0.99/0.61	0.99/0.61
Maximum normal incidence total power (W)**	550/340	270/286
Peak normal incidence power density (W/mm^2)**	550/340	270/286
Allowable thermal induced slope error, within 80% central active length, remove best-fit cylinder (μrad)	<0.1	<0.1
Preferred cooling method	Eutectic Bath	Eutectic Bath
Cooling contact material	InGa eutectic	InGa eutectic
Baking compatibility assembly without mirror/cooling	120°C	120°C
Baking compatibility with mirror/cooling	100°C	100°C
Vacuum pressure at room temperature	< 2• 10^{-9} Torr	< 2• 10^{-9} Torr
Vacuum pressure during operation	< 4• 10^{-9} Torr	< 4• 10^{-9} Torr

The parameters used to calculate these powers listed in Table A5.5.4.1.

* The maximum absorbed power is the power under which the mirrors need to meet all specifications. Beam defined by 0.95 mm × 0.95 mm white beam slit.

**The maximum normal incidence power and peak power densities are the highest powers and densities that may be incident on the mirrors. Beam defined by 2 mm × 1 mm front end aperture.

***Powers are for undulator U23/U14, details are in Table 3.4.1.

3.2 Motion Control

Table 3.2.1

Parameters	Value	
	35-ID-HFM	35-ID-VFM
X Translation Horizontal (motorized motion) (mm) [X_T]		
Range	±10	±35
Resolution*	0.001	0.002
Repeatability	≤ 0.003	≤ 0.005
Y Translation Vertical (motorized motion) (mm) [Y_T]		
Range	±35	±10
Resolution	0.002	0.001
Repeatability	≤ 0.005	≤ 0.003
θ_y Rotation (radians)	**motorized motion w/ fine scale piezo motion**	**motorized motion**
PZT Range	$\pm$1.0e-4	N/A
PZT Resolution	1.0e-7	N/A
Motorized Total Range	-0.002/+0.005	±0.025
Motorized Resolution*	1e-6	2e-5
Motorized Repeatability	≤ 5e-6	≤ 5e-5
θ_x Rotation (radians)	**motorized motion**	**motorized motion w/ fine scale piezo motion**
PZT Range	N/A	$\pm$1.0e-4
PZT Resolution	N/A	1.0e-7
Motorized Total Range	±0.025	-0.002/+0.005
Motorized Resolution*	2e-5	1e-6
Motorized Repeatability	≤ 5e-5	≤ 5e-6
θ_z Rotation (radians)	**Motorized motion**	
Range	±0.01	±0.01
Resolution*	5.0e-6	5.0e-6
Repeatability	≤ 2.0e-5	≤ 2.0e-5

*Resolution=Minimum Step size
Repeatability is unidirectional i.e. when backlash correction is used

3.3 Tolerances

Table 3.3.1

Parameters	Value	
Allowable induced error after horizontal (vertical) translation	35-ID-HFM	35-ID-VFM
X (Y) (mm)	0.005	0.005
θ_z (radians)	≤ 5e-5	≤ 5e-5
θ_y (radians)	≤ 5e-6	≤ 2e-5
θ_x (radians)	≤ 2e-5	≤ 5e-6

Table 3.3.2

Parameters	Value	
Allowable induced error after bending from flat to minimum radius	35-ID-HFM	35-ID-VFM
X (Y) (mm)	0.05	0.05
θ_z (radians)	≤ 5e-5	≤ 5e-5
θ_y(radians)	≤ 5e-6	≤ 2e-5
θ_x (radians)	≤ 2e-5	≤ 5e-6

Table 3.3.3

Parameters*	Values	
Vibrational and Drift Dynamics	35-ID-HFM	35-ID-VFM
Natural vibration frequency of vessel and vessel support structure	>100 Hz	>100 Hz
Natural vibration frequency of mirror bender/support structure	>100 Hz	>100 Hz
θ_x (θ_y) stability (1-2500 Hz) [RMS]	< 100 nrad	< 100 nrad
Long term (>1 hr) θ_x (θ_y) stability [RMS]	< 200 nrad	< 200 nrad

*Specifications measured with x-ray beam are done without feedback

3.4 X-ray specifications

Table 3.4.1

Parameters (For reference only)	Value
Source location (m) (Origin at the center of the straight section)	0
Nominal white-beam height measured from the floor (mm)	1400
Revolver undulator periods (mm)	23/14
Length of undulator (m)	2.3 x 2
Deflection parameter for worst case power K	1.61 (U23) 0.436 (U14)
Number of periods	206/338
Front end aperture size (mmH x mmV)	1.5 x 1.0
Front end aperture location (m)	31.2
White beam slit (mmH x mmV)	1.5 x 1.0
White beam slit location (m)	27.6
35-ID-HFM location (m)	34-35
35-ID-VFM location (m)	36-37
Beam size at the 35-ID-VFM (mmH x mmV) with 1.33mm x 0.88mm WB Slit	1.68 x 1.12
Beam size at the 35-ID-HFM (mmH x mmV) with 1.33mm x 0.88mm WB Slit	1.77 x 1.18

Motions and Controls

All motions for the 35-ID-KB-Mirror will be performed using stepping motors. The vendor shall supply motor drivers controllable with differential step and direction signals. All motion control and limit signals shall be routed to a RJ45 jack (one per motor), and encoding signals routed to a DB9 connector (one per encoder). Both connectors are pinned per the APS standard. The motors/motions will be monitored via encoding devices equipped with limit switches and hard stops. All motors and encoders must be compatible with EPICS http://www.aps.anl.gov/epics/ supported motor controllers (e.g., MAXv VME motor controller cards from OMS Motion: http://www.omsinmotion.com/about_us/). Limit switches must be "normally closed" and both the switches and the hard stops must be accessible for adjustments.

All electrically energized systems shall be listed by a nationally recognized testing laboratory (NRTL). A Nationally Recognized Testing Laboratory list may be found at https://www.osha.gov/dts/otpca/nrtl/nrtllist.html. All connections and terminations need to be NFPA 70 latest edition compliant. If integrated assemblies of electrical components have not been tested, the supplier must be able to demonstrate that the assemblies or individual components have been constructed according to applicable standards such as those associated with Underwriters Laboratories (UL), the American National Standards Institute (ANSI), the Institute of Electrical and Electronic Engineers (IEEE), the National Electrical Manufacturers Association (NEMA), Semiconductor Equipment Manufacturers International (SEMI), or comparable standards organizations located outside the United States. If the system is not listed by a NRTL it will be inspected by the Argonne DEEI program

3.5 Cooling

The 35-ID-HFM and 35-ID-VFM mirrors will be bendable and a slot/trough eutectic-bath cooling scheme is preferred. If however examples are provided of alternative cooling methods for bendable mirrors that are able to meet all other specifications then these methods will be considered.

All cooling methods and geometries must be designed to reduce the thermally induced slope error in the worst-case operational power load listed in Table 3.1.2. A relative pitch stability of < 100 nrad is required in a frequency range of 1-2500 Hz RMS, even with the chiller operating and water flowing through the cooling lines at the maximum expected flow rate.

The temperature of each mirror and mask must be monitored via type K thermocouples, attached in regular distances along the length of the component, and connected to the outside of the vacuum chamber via vacuum feedthroughs.

3.6 Mirror Masks and Compton Shielding

Water-cooled masks are needed to protect the upstream face of each mirror from miss-steered beam exposure. Water piping should be designed to be in accordance with ASME B31.3. These masks shall be located inside the mirror tanks, their shallow edges protruding beyond the upstream edges of the mirrors by a few microns, carefully aligned so as not to shadow the useful length of the mirrors above a mirror angle of 1 mrad. The masks shall be water cooled with no water-to-vacuum joints. The masks must be able to withstand the maximum incident power within a given beam and they shall be equipped with type K thermocouples for temperature measurement. The maximum incident total power to the 35-ID-HFM is 550 W with a peak nominal incidence power density of 550 (W/mm^2). This calculation is based on the total power through the 1.5 mm x 1 mm front end aperture with the minimum closed gap of the 23 mm period undulators. The total maximum incident total power to the 35-ID-VFM is 290 W with a peak nominal incidence power density of 290 (W/mm^2). This calculation is based on the total reflected power by Pt stripe of the 35-ID-HFM set (1000 mm physical length) at 2.1 mrad incidence, with the maximum closed gap of the U14 mm period undulators. All other relevant parameters are listed in Table 3.4.1.

Compton scattering is a significant source of heat. When scattered radiation strikes a mirror support, the component could drift, resulting in a change of the mirror angle. The mirror supports therefore shall be designed to minimize exposure to scattered radiation and be protected by the placement of appropriate shields. Compton shields should be water-cooled, and thermocouples should be in place to monitor their temperature.

3.7 Support Structure

The mirrors should be connected to the beamline vacuum port through bellows at the 35-ID-A station. The mirrors should be mounted on stable support structure(s) such that ground vibrations are not significantly amplified. In a laboratory environment where the temperature is stabilized to +/- 0.5°C, the pitch angle of each mirror system should not drift by more than 0.5 μrad over a 24-hr period.

The vendor shall propose a method for coupling the support structure to the experimental hall floor. The APS is currently investigating various methods for coupling the mirror base to the floor. Based on this study, the APS reserves the option to change the coupling method at the final design milestone (Section 1.5.3).

The chamber and support must include lugs/eyes for lifting. In the highest position, the 35-ID-A crane hook is about 5 m from the floor. The 35-ID-A crane has a load capacity of 2000 pounds.

3.8 Space and Height Requirements

The 35-ID-KB-Mirror system is located at the entrance of the 35-ID-A hutch. The center of the first mirror (horizontal mirror) center at ~ 34 m. The maximum inboard extension of the mirror system from the X-ray beam shall be no greater than 1000 mm. The maximum outboard extension of the mirror system from the X-ray beam shall be no greater than 1000 mm. The maximum available length for the mirror system is 4000. The total length of the mirror systems from flange to flange should be less than or equal to 3500 mm. The nominal beam height at the first mirror location is 1400 mm from the ground. Designs that require minor deviations from the suggested footprint will also be reviewed.

3.9 Mirror Benders

Mirrors shall be equipped with two-moment mechanical benders to achieve an elliptical surface in the tangential plane. The minimum bending radius should ensure focus at the minimum sample location shown in Table 3.1.1. Absolute encoder(s) shall be provided to ensure the repeatability and stability of the bending mechanism. An example of the absolute encoder is Resolute™ Encoder series by Renishaw Apply Innovation. The minimum bending radius should be attained with repeatability better than 5%. Once the user has selected or adjusted the desired bending, the new bending radius should be fixed and stable to better than 2% over 24 hrs. The mirror bender shall provide continuous bending from flat to the maximum bending with different focal positions. When un-bent, the mirror surface should be flat (as specified in Sect. 3.1, flat means tangential R > 300 km and sagittal R > 20 km).

The bender shall be equipped with a twist angle adjustment motion if the twist angle specification in Table 3.1.1 cannot be satisfied. A manual twist adjustment (or shimming correction) is required for the initial mounting and alignment of the mirror in the mirror bender so that the twist angle is <100 μrad. If this twist angle specification (<100 μrad) cannot be satisfied in the entire bending range (4 km to flat), a motorized twist angle adjustment shall be required.

3.10 Vacuum and Ports

3.10.1 Vacuum

Design, material, fabrication, cleaning, handling, tests, and packaging of the vacuum system and components shall conform to the following APS documents included as attachments with this SOW:

- APS ICMS Document No. APS_2018473, *APS-U Engineering Standard Vacuum Designs*
- APS ICMS Document No. APS_066006, *Technical Specification for Fabrication of UHV Front End and Beamline Components, Revision 1.*

All parts of the 35-ID-KB-Mirror system, such as motor wiring and other non-metal materials, in-vacuum motion parts, viewports etc. must be compatible with ultra-high vacuum (UHV) standards. On bolted joints, the bottom of the tapped hole and the annular space around the shank of the bolt in the thru-hole section of the joint must both be vented.

All flanges must be Conflats, manufactured from 304 or 316 stainless steel and sealed with copper gaskets, except for the large vessel flange(s) that may use a viton seal as long as the Viton is well shielded from radiation (e.g. a cm or more of stainless steel flange). The vessel must be fabricated from dull polished 304 grade stainless steel plates with full penetration welds, cleaned, and prepared in accordance with standard UHV requirements.

The base pressure for the 35-ID-KB-Mirror chamber without internal components must be less than $1x10^{-8}$ Torr at room temperature.

Prior to shipping, the vendor shall assemble, pump down, and vacuum test the entire UHV assembly.

Organic adhesives and sealants, which could result in contamination of the mirror surfaces, shall not be incorporated into the in-vacuum assembly. Material that degrades under the radiation environment encountered in an APS undulator beamline shall not be used for the mounting fixtures and attachments. All materials used, including in-vacuum labeling of components, must be disclosed to and approved by the APS technical representative. No direct liquid-to-vacuum seals are allowed inside the chambers.

To allow compatibility with the beamline vacuum system, the vendor will supply ion pumps from Gamma Vacuum LLC, and either cold cathode gauges from Televac or hot cathode gauges from Granville-Phillips. The vendor must submit the ion pump and controller model numbers to the APS for approval prior to purchasing. The ion pump and the ion gauge shall not be positioned in a direct line of sight to the optical surfaces of the mirrors. Protect knife-edges from dents, nicks, and scratches and protect flanges with foil and plastic caps.

3.10.2 Ports

The vacuum chamber shall have the following CF ports: 6" beam inlet and outlet, vacuum pump port, turbo pump, RGA, ion gauge, roughing venting and leak-check, viewports (3), spare 2-3/4" (2).

Inspection windows shall be placed such that there is a clear view of the mirror surfaces from the exterior of the vacuum chamber. These windows shall be quartz to avoid discoloration due to radiation damage. A third window should be positioned to illuminate the interior of the vacuum chamber.

3.11 X-ray window for X-ray in and out

The beam entrance flange of the 35-ID-KB-Mirror will be connected to the beamline vacuum pipe at the 35-ID-A station through bellows with a gate valve. The beam exits from mirror through an 6-inch CF flange. During vacuum testing and shipping, an 6" blank shall be used.

3.12 Vacuum components and Tasks Provided by APS

Calibrated vacuum instruments and equipment are required for factory acceptance testing at the fabrication facility. The vendor shall provide a list of equipment and instruments to be used for factory acceptance testing for approval by the APS prior to use. The vacuum instruments and equipment shall be calibrated and traceable to the U.S. National Institute of Standards and Technology or equivalent standards laboratory. The vendor shall provide copies of the calibration certificates or records for the equipment being used to perform the acceptance tests. APS will provide the instruments for leak testing and pump down at the APS site during vendor installation.

4 Quality Assurance and Inspection

The vendor shall adhere to all quality control requirements as specified in this document and the accompanying Quality Assurance Procurement Requirements Form ANL-407. Any deviations from this Statement of Work shall be approved in writing using an APS Upgrade Project Supplier Disposition Request form included in the Argonne purchase order.

5 Packing and Shipping

The vendor shall adhere to all packing and shipping requirement as specified in this document and the accompanying Quality Assurance Procurement Requirements Form ANL-407.

The vendor is responsible for the proper packing and shipping of all components. The 35-ID-KB-Mirror will be used in a UHV environment and shall remain HV clean during shipping.

The mirrors and the chambers must be packaged in separate containers. The mirrors must be securely fastened in hermetically sealed shipping containers to prevent chafing that could damage the mirror and/or generate contaminating particles. The vacuum chambers shall be sealed with blank flanges. The assemblies shall be securely fastened, padded, boxed, and crated.

The crates shall be suitable for lifting and transportation without damage using a forklift or crane during delivery. They must allow storage of the items for a period of 3 months in an indoor environment.

The vendor shall prepare a plan describing the shipping, lifting, and handling of the assemblies. APS shall review and approve the plan prior to shipment.

Each shipping container shall also contain the quality assurance records specified in the ANL-407 form.

For shipping from other countries, the vendor shall use an experienced customs agent or customs bonded freight forwarder.

6 Mirror System Acceptance Tests

6.1 Inspection and Factory Acceptance Tests (FAT)

The APS-U reserves the option to be present (physically or virtually) during factory acceptance testing of the mirror system. The vendor shall give at least an 8-week notice prior to any factory test date to allow for the necessary travel arrangements to be made.

The mirror system shall be fully tested at the vendor's facilities prior to delivery to APS. The factory acceptance test procedures shall be prepared in advance and submitted to APS for approval before starting the testing work. The test results must demonstrate that all specifications described in Section 3 have been met. All tests must be properly recorded on test certificates and the results submitted to the APS-U Technical Representative for approval.

These reports shall contain the signature and title of the authorized contract representative of the agency performing the tests and shall be approved by Supplier Quality Assurance. The data submitted shall also be transmitted in electronic PDF format to the APS-U technical representative. Any non-conformances resulting from the testing process shall be reported in writing using and APS Upgrade Project Supplier Disposition request form included in the Argonne purchase order within 72 hours of discovery.

6.1.1 Vendor-based Optical Metrology Measurements

Mirror figure errors and surface micro-roughness must be measured by the vendor after polishing and coating. The vendor shall prepare a plan describing the metrology techniques. The APS-U Technical Representative shall review and approve the plan prior to implementation. If a subcontractor is used to manufacture the mirror substrate, these measurements shall be carried out by the subcontractor and the results shall be approved by APS-U prior to delivery of the substrate to the vendor.

The vendor shall provide the coating thickness measurement of a witness sample that was coated at the same time as the mirror. Alternatively, the vendor can ship such a sample to APS for verification and quality control by APS qualified staff.

The metrology data collection requirements are given below

- Tangential slope errors
  - Measured over the range: 1 mm – full active length
  - Parallel line scans along tangential direction, minimum of 5 scan lines, cover the entire active width, measurements shall be performed after coating. The measurement lines should be parallel to the central line of the mirror surface within 1 mrad.
- Sagittal slope errors
  - Measured over the range: 1 mm – full active width
  - Parallel line scans along the sagittal direction, a minimum of 5 scan lines, cover the entire active length.
- Roughness
  - Measured over the range: 1 μm – 1 mm
  - Measured at a minimum of 10 (ten) randomly distributed locations within the active area, recording (approximately) the measurement location. Measurements shall be performed after coating.

The mirror figure errors and surface roughness specifications are listed in Table 3.1.1. A few general requirements are listed below:

- There should be no dominant peaks in the power spectral density of the tangential figure errors
- <0.5 scratches or pits per cm^2 to the unaided eye
  - within the active area
  - under illuminance of 15000 lumen/m^2 or greater
  - for all possible relative positions of inspection lighting and observation

6.1.2 Mechanical Testing

All motorized motions shall be tested and verified to be in conformance with Tables 3.2.1, 3.3.1, and 3.3.2.

6.1.3 Vibration Testing

The vendor shall perform vibration measurements on the mirror to demonstrate that the mirror assembly meets the tolerances listed in Table 3.3.3. The intention is for the vendor to consider the vibration performance during the design process. The APS floor vibrations are quantified in the attached document: "A Survey of Floor Vibration Noise at all Sectors in the APS Experiment Hall," LS-344, S. Kearney, and D. Shu. ICMS Document No. APS_1699863. The average data across all sectors, shown in Figure 2 of the document, should be used to inform the mirror design. These data are also available electronically.

The lowest natural frequency (eigenfrequency) of the entire mechanical system, including the support structure, shall be greater than 100 Hz. A relatively high eigenfrequency of 100 Hz will not be excited by floor vibrations that are typically lower than 40 Hz at the APS.

For all vibration tests, the mirror shall be mounted as installed at the APS. The vendor will grout a floor plate to their workshop floor in a manner similar to the final installation. While the floor vibrations and stiffness will be different than the APS experimental hall floor, this will minimize spurious vibrations and make interpretation of the FAT vibration tests more reliable. The APS-U understands that the vendor may be manufacturing numerous mirrors for the APS, some with differing base geometries. A generic floor plate may be used that incorporates T-slots or other means of accommodating the mounting of each mirror. The goals are to 1) ensure the floor plate is secured to the floor, and 2) ensure the mirror is secured to the floor plate.

The APS-U shall be notified at least 8 weeks in advance of the tests. An APS-U staff member can be made available at no cost to the vendor to assist with the vibration tests at the factory.

The vendor shall use the following equipment and procedures **or equivalent** for the measurements, and the vendor is free to suggest a comparable testing routine:

- A data acquisition (DAQ) system with a sampling rate of at least 6400 Hz. The DAQ system shall have an analog anti-aliasing filter such that an alias-free bandwidth of 1 to 2500 Hz is available. The DAQ system will be able to acquire a block of data that is 327680 samples long or smaller blocks of 32768 blocks, ten in succession. The DAQ system will be able to acquire a minimum of three simultaneous channels of data.
- On-mirror vibration shall be measured with PCB 393B05 accelerometers or equivalent.
- Floor vibration shall be measured with PCB 393B31 or equivalent.
- Impact measurements to determine the first natural frequency shall be done using a PCB 086C01 impact hammer or equivalent.
- An orthogonal block shall be necessary to mount the accelerometer for in-plane floor vibration measurements.
- Accelerometers shall be wax (or CA glue) mounted on clean and smooth surfaces. Alternatively, the accelerometers can be mounted using 10-32 or ¼”-28 studs, as appropriate.
- Before any FFT operation, the data shall be windowed using a Hanning window applied to each 32768 element block. The ten PSDs shall be averaged.

The vendor shall make the following measurements and vibration data analyses:

- Simultaneous ambient vibration level measurements of the floor and the mirror support base.
- Simultaneous ambient vibration level measurements of the floor and a point on the mirror tank. The point of measurement shall be marked on a drawing, picture, or diagram of the mirror assembly.
- Simultaneous ambient vibration level measurements of the floor and the mirror (mirror surrogate or on the mirror holder are acceptable). Time domain calculations shall be used to determine the pitch motions from the two mirror-mounted accelerometers.
- The data from the three vibration level measurements above shall all be processed and included in the testing report in three ways:
    - The square root of the displacement PSD from 1-2500 Hz in each of the X, Y, and Z directions.
    - The integrated RMS displacement, integrated from high frequencies to low frequencies, in each of the X, Y, and Z directions, shown on a 1-2500 Hz bandwidth. See Attachment [4].
    - The magnitude of the transmissibility between the floor and the mirror in each of the X, Y, and Z directions. This is defined as the ratio of the PSD of the support base motion to the PSD of the floor motion.
- Impact frequency response function (FRF) measurements of the mirror to determine the pitch natural frequencies. The 393B05 accelerometers (or equivalent) shall be mounted in the same location as for the ambient mirror vibration measurements (in the pitch direction). The impact hammer will be used to tap the mirror surrogate or mirror holder normal to the mirror. The hammer signal and two accelerometer signals will be recorded simultaneously. A minimum of three averages shall be carried out. A sampling frequency of 512 Hz can be used and 1024 data points can be acquired. No windowing should be used. The number of data points can be increased as necessary to ensure the response decays to zero at the end of the data block. These data shall be processed and included in the testing report as follows:
    - The magnitude and phase (Bode plot) of FRF between the hammer and each accelerometer.
    - The coherence function between the hammer and each accelerometer.

6.1.4 Vacuum Integrity

The base pressure shall be measured using cold cathode gauges from Televac or hot cathode gauges from Granville-Phillips or equivalent. The base pressure for the 35-ID-KB-Mirror vacuum chamber must be less than $2x10^{-8}$ Torr at room temperature. The helium leak rate must be less than $2x10^{-10}$ mbar L/s when the part is surrounded by helium for 3 minutes. The leak-rate background should be measured before the vessel is exposed to helium.

6.2 Acceptance Tests Performed at the APS

The vendor shall include in their proposal a quote for the cost of engineering support to setup, measure, and calibrate the mirror-bender system at the APS in the APS Optics Laboratory prior to installation on the beamline. The acceptance tests will be used to determine compliance with the specifications listed in Section 3.

Acceptance tests will include measurements of the following properties:

- Surface Roughness (APS responsibility)
- Tangential and sagittal slope error and radius tolerances (APS responsibility)
- Bender calibration and characterization (APS responsibility)
- Allowable mirror twist angle during bending between flat and the nominal focusing (APS responsibility)
- Allowable induced error after y translation (vendor Responsibility with APS Present)
- Allowable induced error during bending between flat and the nominal focusing (vendor Responsibility with APS Present)
- Vibrations (vendor Responsibility with APS Present, see Section 6.1.3)
- Vacuum Integrity (vendor Responsibility with APS Present, see Section 6.1.4)
- Motion controls, encoders, and sensors (vendor Responsibility with APS Present)

6.2.1 Surface Roughness

Surface roughness will be measured using a calibrated phase-shifting microscope interferometer - a Zygo NexView™ system. Two different objective lenses with different magnifications (50× and 5.5×) will be used. The 50× objective lens has a 0.52 µm resolution and a field of view of 246 µm × 246 µm. The 5.5× has a 1.99 µm resolution and a field of view of about 2.4 mm × 2.4 mm. NexView™ has a zoom capability of 0.5×, 1×, and 2×.

The mirror surface clear aperture will be measured at 10 randomly selected spots. Raw 2-D data will have tilt and power subtracted prior to RMS roughness calculation and averaging.

6.2.2 Tangential and Sagittal slope error

The figure error measurements will be performed using a combination of slope-measuring profilometry and 2-D phase measuring Fizeau and microscope interferometry with sub-aperture stitching. Slope error data will be acquired using the upgraded APS slope measuring system, which is equipped with three autocollimator-based slope sensors operating in the Nanometer Optical Measuring (NOM) measurement mode. The system has an angle resolution of 20 nrad rms. Multiple measurements will be carried out and integrated to extract the mirror height profile. 2-D phase measurements will be carried out using the calibrated Zygo Verifre™ HDX interferometer at normal incidence for <150 mm and at grazing incidence for the longer mirrors.

Where required, micro-stitched superaperture measurements will be performed using the APS NexView™ profiler, which will be equipped with a 2.75× objective lens, which has 3.56 μm optical resolution and a field of view up to 6 mm × 6 mm.

The mirrors will be evaluated in their mounting support and deflecting configuration as specified in this SOW. The above measurements will be used to verify vendor measurement and determine compliance with the specifications.

6.2.3 Bender Calibration and Characterization

The bender calibration shall be carried out at the APS Metrology Facility with a vendor representative present to assemble the bender and mount the mirror substrate. If there are schedule conflicts with the APS metrology facility, a third-party facility may be contracted. The following parameters will be measured:

- NOM profiling will provide tangential slope error data at nominal focusing radius
- Hysteresis and repeatability will be conducted. These tests will include 5 cycles from unbent to the nominal focusing condition
- A calibration curve between the encoders and the bent mirror shape will be measured
- Stability over 24 hours will be measured at the nominal focusing condition
- Parasitic motions in θ_x, θ_y, θ_z and translation during bending between flat and the nominal focusing condition will be measured

7 Installation, Alignment and Testing

7.1 On-Site Assembly and Installation

On-site assembly of the 35-ID-KB-Mirror system, including the installation of the optics into the 35-ID-KB-Mirror system and acceptance testing and installation of the 35-ID-KB-Mirror systems into the beamline, will be carried out by the vendor. At least one vendor technician shall be available for eight working days. Beamline representatives and APS staff will be available to assist in the acceptance and installation process. The vendor shall supply a handling and rigging plan. The vendor will submit a service contract Job Safety Analysis (JSA) for this work activity as a high-risk service contract. Upon arrival at ANL, vendor personnel shall take ANL Contractor Safety Training and satisfy all APS-U safety requirements before beginning installation and any other work activities associated with the installation and testing procedures. A half-day shall be allocated at the beginning of the installation for ANL Contractor Safety Training and a pre-job safety briefing and inspection.

All motion components, vacuum and mechanical fabricated components, and their assembly must be inspected by the vendor at the APS for damage and wear before testing and site installation.

During installation and testing, the APS will supply the following vacuum related items/equipment: Vacuum components such as turbo pumps, leak checker, valves, vacuum gauges, cables, power supplies, controllers, pressure read-out electronics, and right-angle valves.

7.2 Alignment Relative to the X-ray Beam

The design of the 35-ID-KB-Mirror chamber shall have an easy means to align the mirrors relative to the X-ray beam. Prior to alignment, the APS Survey and Alignment Group will fiducialize the mirror surface in its nominal position. Fiducials located on the main support structure of the mirror will be referenced to the mirror's planar surface and orientation with respect to the nominal beam centerline. The fiducials should be easily accessible, distributed widely across the component and as near to the position of the adjustment mechanisms as possible to increase the accuracy. A line of sight to the mirror surface should be provided such that a Laser Autocollimator can measure the mirror θ_Z and θ_X (θ_Y). Support from the APS survey group will be available during installation.

Machined features that may be utilized as fiducials include:

- Machined flat faces orthogonal with respect to features of importance, with a GD&T flatness tolerance zone of <0.05 mm across the surface area
- Precision holes with a precise diameter of 0.2500"; +0.0003" / -0.0000" drilled normal to a flat seating surface. The flat surface must meet the "machined flat" tolerance given above. The holes will accept various alignment fixtures for use with laser trackers, CMM arms, and/or optical instruments.

Fixed, prefabricated fiducial monuments are commercially available and are preferred, as they provide increased measurement repeatability and reproducibility. The monuments may be permanently welded to a component or adhered with glue. Vendors include:

- Hubb's Machine and Manufacturing
- Brunson Instrument Company

The placement of and the number of fiducial points will be approved by the APS Survey and Alignment group as part of the PDR and FDR described in Sections 1.5.2 and 1.5.3.

7.3 On-site Mechanical Testing

Motion testing of all motorized axes, pump-down, vacuum, and pressure testing of all fittings and seals will be carried out by the vendor after installation. Helium leak checking to 2 x10^{-10} mbar L/s will be done using an APS Leak Detector.

Attachments

[1] "APS Engineering Standard vacuum Designs", ICMS Document No.: APS_2018473.

[2] "Technical Specification for Fabrication of UHV Front End and Beamline Components", Revision 1. APS ICMS Document No. APS_066006

[3] "A Survey of Floor Vibration Noise at all Sectors in the APS Experiment Hall," LS-344, S. Kearney and D. Shu. ICMS Document No. APS_1699863

[4] Martin D. Kochanczyk, Tobias F. Bartsch, Katja M. Taute, Ernst-Ludwig Florin, "Power spectral density integration analysis and its application to large bandwidth, high precision position measurements," Proc. SPIE 8458, Optical Trapping and Optical Micromanipulation IX, 84580H (10 October 2012); doi: 10.1117/12.929349

[5] APS Upgrade Project ANL-407 Procurement Quality Assurance form.