Engineering Specifications for the XTOD Hard X-Ray Offset Mirrors

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Brief Summary: This document establishes specifications/requirements for the fabrication and inspection of mirrors for the X-Ray Transport Optics and Diagnostics (XTOD) group Hard X-Ray Offset Mirror System (HOMS).

Change History Log

<table>
<thead>
<tr>
<th>Rev Number</th>
<th>Revision Date</th>
<th>Sections Affected</th>
<th>Description of Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>2007/9/6</td>
<td>All</td>
<td>Initial Version</td>
</tr>
<tr>
<td>001</td>
<td>2007/11/9</td>
<td>2.2.1, 2.2.2.2, 2.3.1, 2.3.2, 2.3.5.1, 2.3.6, and 3.4.</td>
<td>Increased tangential surface radius, reduce size of clear aperture Zone 2, specify silicon substrate crystal orientation, modify requirements for Handling and Process Plan, include requirements for test coupons and substrate.</td>
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</table>
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Appendix A: Mirror Specification Summary
1. **Scope**
   This document establishes specifications/requirements for the fabrication and inspection of mirrors for the X-Ray Transport Optics and Diagnostics (XTOD) group Hard X-Ray Offset Mirror System (HOMS). The HOMS is a two-mirror optical system designed to substantially reduce the levels of high-energy spontaneous radiation, Bremsstrahlung γ-rays and their secondary radiations within the experimental halls of the Linac Coherent Light Source (LCLS) at the Stanford Linear Accelerator Center (SLAC). At the same time, the XTOD HOMS should minimally degrade the intrinsic characteristics of the LCLS FEL beam.

2. **Requirements**

2.1 **Mirror Definition**
   The mirrors are described by the LCLS/LLNL Drawing and by Section 2 of the present document. They have a tangential cylinder optical surface.

2.2 **Design Characteristics**

2.2.1 **Surface Figure Definition and Tolerances**
   A pictorial definition of relevant terminology is given in Figure 1.

![Figure 1: Pictorial definition of terminology](image)

Mirror optical parameters:

<table>
<thead>
<tr>
<th><strong>Surface Radius</strong></th>
<th><strong>Specification</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangential</td>
<td>$150 \text{ km} \leq R_{\text{Tan}} \leq 195 \text{ km}$</td>
</tr>
<tr>
<td>Sagittal</td>
<td>$&gt; 4 \text{ km}$</td>
</tr>
</tbody>
</table>

Check the LCLS Project website to verify that this is the correct version prior to use.
The LCLS/LLNL Drawing\(^2\) includes the following information:

Mirror geometrical size and features
Tolerances of: size, location, form, and orientation

2.2.2 Optical Surface Quality Requirements

2.2.2.1 Measurement Area and Locations
The optical surface specifications defined herein shall be applied within the "clear aperture zones" defined quantitatively in Figure 2.

2.2.2.2 Figure errors
The following requirements apply:

<table>
<thead>
<tr>
<th>Clear Aperture</th>
<th>Figure Error</th>
<th>Specification</th>
<th>Measurement Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height Error</td>
<td>≤ 2.0 nm rms</td>
<td>Spatial Frequency: 2.6 ( \times 10^6 ) ( \mu \text{m}^{-1} ) to 10(^{-3}) ( \mu \text{m}^{-1} ), Error Wavelength: 1 mm to 385 mm</td>
</tr>
<tr>
<td>Zone 1</td>
<td>Tangential Slope Error</td>
<td>≤ 0.25 ( \mu \text{rad} ) rms</td>
<td>Spatial Frequency: 2.6 ( \times 10^6 ) ( \mu \text{m}^{-1} ) to 10(^{-3}) ( \mu \text{m}^{-1} ), Error Wavelength: 1 mm to 385 mm</td>
</tr>
<tr>
<td></td>
<td>Sagittal Slope Error</td>
<td>≤ 2 ( \mu \text{rad} ) rms</td>
<td>Spatial Frequency: 2.0 ( \times 10^4 ) ( \mu \text{m}^{-1} ) to 10(^{-3}) ( \mu \text{m}^{-1} ), Error Wavelength: 1 mm to 5 mm</td>
</tr>
<tr>
<td>Zone 2</td>
<td>Height Error</td>
<td>≤ 5.0 nm rms</td>
<td>Spatial Frequency: 2.3 ( \times 10^6 ) ( \mu \text{m}^{-1} ) to 10(^{-3}) ( \mu \text{m}^{-1} ), Error Wavelength: 1 mm to 430 mm</td>
</tr>
<tr>
<td></td>
<td>Tangential Slope Error</td>
<td>≤ 0.63 ( \mu \text{rad} ) rms</td>
<td>Spatial Frequency: 2.3 ( \times 10^6 ) ( \mu \text{m}^{-1} ) to 10(^{-3}) ( \mu \text{m}^{-1} ), Error Wavelength: 1 mm to 430 mm</td>
</tr>
<tr>
<td></td>
<td>Sagittal Slope Error</td>
<td>≤ 2 ( \mu \text{rad} ) rms</td>
<td>Spatial Frequency: 6.7 ( \times 10^5 ) ( \mu \text{m}^{-1} ) to 10(^{-3}) ( \mu \text{m}^{-1} ), Error Wavelength: 1 mm to 15 mm</td>
</tr>
</tbody>
</table>

The aforementioned height and slope errors are determined after subtraction of best-fit cylinder reference surfaces from the clear aperture zone. Best-fit cylinder radii, tangential or sagittal, must meet the respective surface radii specifications in Section 2.2.1 above.

Full-aperture, visible-light interferometry will be used to determine the surface figure at the vendor’s facility, after processing of the mirror surface has been completed. Verification of the mirror figure will take place at LLNL using the LLNL full-aperture interferometer.

Notes:
(1) It is the vendor’s responsibility to demonstrate that the effects of interferometer measurement error and gravity distortion are either negligible or are removed from the data.
2.2.2.3 Roughness

<table>
<thead>
<tr>
<th>Roughness</th>
<th>Specification</th>
<th>Measurement Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Spatial</td>
<td>≤ 0.25 nm rms</td>
<td>10⁻³ μm⁻¹ to 0.5 μm⁻¹</td>
</tr>
<tr>
<td>High-Spatial</td>
<td>≤ 0.4 nm rms</td>
<td>0.5 μm⁻¹ to 50 μm⁻¹</td>
</tr>
</tbody>
</table>

See Figure 2 below for locations of roughness measurement sites. The roughness measured at each site shall be compared for compliance with the specifications.

Roughness shall be measured on each mirror after cleaning. A visible-light interferometer or profilometer will be used for mid-spatial frequency measurements at the vendor’s facility. If available, an AFM instrument will be used for high-spatial frequency measurements at the vendor’s facility. If an AFM instrument is unavailable, alternative arrangements must be made with LLNL. Verification of the mid-spatial frequency roughness and the high-spatial frequency roughness will take place at LLNL using the LLNL white-light optical profiling microscope and the LLNL AFM instrument.

2.3 Design and Construction

2.3.1 Substrate Material

The mirror substrate material will be single-crystal silicon, with a <100> direction oriented along the "Length" of the mirror, as defined in Figure 1, above. It shall additionally be free from defects such as dislocations, cracks, etc. Its resistivity shall be ≤ 10 Ω-cm.
2.3.2 Surface Finish

2.3.2.1 Optical Surface Area

The mirror optical surface shall be finished using a controlled grinding and polishing process to remove residual sub-surface damage and leave the optical surface in a stress-free condition.

The mirror optical surface shall have no striae under visible examination.

The mirror optical surface shall meet a scratch/dig requirement of 10/5 per MIL-PRF-13830B.

2.3.2.2 Non-Optical Surface Areas

The mirror non-optical surface areas shall be finished using a controlled grinding process followed by wet-chemical etching to remove residual sub-surface damage and leave the non-optical surface areas in a stress-free condition. This process shall be staged such that all surfaces of the completed mirror, with the exception of the optical surface, shall be wet-chemical-etched surfaces.

2.3.3 Workmanship

Workmanship shall be consistent with the quality necessary for stable operation of sensitive optical devices under long-term exposure to an x-ray, ultrahigh vacuum (UHV) environment similar to that found in synchrotron radiation user facilities.

2.3.4 Handling and Cleaning

**Handling:** Full, UHV handling practice is required. Each mirror shall be handled in accordance with the Handling and Process Plan, as reviewed and approved by LLNL.

**Cleaning:** Each mirror shall be cleaned at the vendor’s facility in a manner that is consistent with the figure, mid- and high-spatial frequency roughness requirements discussed in this document and that allows the mid- and high-spatial frequency roughness to be evaluated. Cleaning shall be performed at the vendor’s facility in accordance with the methods outlined in the Handling and Process Plan provided by the vendor and approved by LLNL.
2.3.5 Packaging and Shipping

The vendor shall be responsible for design and fabrication of the mirror shipping container(s). Best protection against contamination and shock/vibration is essential. An all-metal, dust-free interior-most enclosure is desirable. Include a brief description of proposed packaging and shipping arrangements in the Handling and Process Plan.

2.3.5.1 Test Coupon Packaging and Shipping

The vendor shall be responsible for supplying test coupon shipping container(s) (see Section 3.4.1). Best protection against contamination and shock/vibration is desirable. A dust-free interior, sealed enclosure is desirable. Coupons are to be restrained at the edges of the polished surface, to preserve the surface condition. Include a brief description of proposed packaging and shipping arrangements in the Handling and Process Plan.

2.3.6 Handling and Process Plan

All mirror processing shall take place in accordance with the methods described in the vendor-supplied Handling and Process Plan. This document shall be provided in response to the Request for Quotation from LLNL, and must be reviewed and approved by LLNL. In that way, any materials compatibility issues for the completed mirrors can be identified and settled in advance. As noted in the sections above, the Handling and Process Plan shall include brief descriptions of the following:
(1) UHV handling procedures
(2) Mirror cleaning procedure
(3) Packaging and shipping arrangements

3 Quality Assurance Provisions

3.1 General

The vendor shall maintain documentation for all metrology and processes during fabrication and characterization of these mirrors.

3.1.1 Responsibility for Inspection and Tests

The responsibility for performing and documenting all specified tests and metrology shall rest with the vendor unless noted otherwise. The vendor shall submit an Inspection Test Procedure to LLNL for approval, as outlined in Section 3.3, describing each test or measurement to be implemented. LLNL reserves the right to perform in-process inspections at the vendor’s facility. The vendor shall
notify LLNL a minimum of 5 working days prior to the start of final inspection and testing. Drawings and equipment that may be required for adequate inspection and test shall be made available to LLNL. LLNL inspection shall in no way relieve the vendor of responsibility for ensuring the quality of the mirrors.

3.1.2 Inspection Test Procedure

The vendor shall prepare an Inspection Test Procedure in response to the Request for Quotation from LLNL. It must be reviewed and approved by LLNL, and shall include the following at a minimum:

1. Proposed tests and measurements to be performed and their method of accomplishment
2. Sequence of measurements, both in-process and final
3. Equipment to be used
4. Accuracy of measurements
5. Calibration techniques
6. Proposed data sheets of results and data format for the Inspection Test Report

3.1.3 In-Process Inspection Points

Vendor in-process inspection points shall be specified as part of the Inspection Test Procedure (see Section 3.1.2). At a minimum, inspections shall be performed at the following points:

1. After initial shaping of the non-optical surface areas
2. Selected points during mirror surface polishing
3. Final inspection after the mirror is finished

3.2 Quality Conformance Inspections

3.2.1 Visual Inspection

The completed mirrors shall be visually inspected for conformance to the requirements in Section 2.3, prior to performing the measurements described in Section 3.2.2. If visual inspections uncover defects, additional inspections and measurements, as needed, shall be performed to determine acceptability. Visual inspections shall use techniques that enhance the visibility of defects, and shall be described in the Inspection Test Procedure (Section 3.1.2.). Illumination of the surface shall be 200 or more foot-candles (lumens per square foot). The mirror shall be viewed against a dark background and from a direction just off the line of specular reflection.

Mirror polish shall be evaluated by visual inspection. Areas with scratches, or pits in excess of the requirements of Section 2.3.2 are unacceptable.
Optical surface edges shall be visually inspected for digs and chips.
Overall appearance shall be free from all visible contamination and poor workmanship indications.

3.2.2 Characterization Metrology

Compliance with the Optical Surface Quality Requirements specified in Section 2.2.2 shall be demonstrated through measurements, and the resulting data provided in the Inspection Test Report. As also stated in Section 3.1.2, all measurement procedures must be proposed-to and approved-by LLNL prior to execution.

Measurements shall be made under the following environmental conditions:
Temperature: 20°C ± 2°C.
Humidity: 30% to 70% relative humidity (RH)
During all measurements, the article under test and the test equipment shall be in thermal equilibrium within the specified temperature range.

Mid- and high-spatial frequency roughness shall be measured at the locations specified in Figure 2. These measurements shall be made after cleaning of the mirrors, as also discussed in Sections 2.2.2.3.and 2.3.4.

Instrumentation used for the measurement of figure, mid- and high- spatial frequency roughness should be capable of accurately measuring the spatial frequency bandwidths specified in Sections 2.2.2.2.and 2.2.2.3., respectively. All equipment should be in current and traceable calibration.

3.3 Inspection Test Report

The vendor shall submit an Inspection Test Report of metrology results and associated raw data with each mirror at the time of delivery.

The Inspection Test Report shall include machine-readable raw data sets for all metrology performed. Data sets shall be in plain ASCII text, or another widely-used format of mutual agreement. The vendor shall describe the file formats and supply necessary constants and parameters to permit independent data analysis of the raw data.
3.4 Test Coupons and Substrate

3.4.1 Test Coupons for Coating Qualification:

Vendor shall provide three single-crystal silicon test polishing coupons, for qualification of the LLNL reflective coating deposition process. In order to make use of LLNL standard tooling, these test coupons should preferably be 2 inch-diameter flat disks with a thickness of 3/8 inch. The exact shape and dimensions (including thickness) of the coupons are at the discretion of the vendor, but subject to negotiation and approval by LLNL. Each test coupon shall be polished/figured using the same processes to be applied on the full-size mirrors. The optical surface roughness in the mid-spatial and high-spatial ranges should meet the requirements in the Section 2.2.2.3. The specification for the surface figure is relaxed to only include a peak-valley surface height error of \( \leq 158 \text{ nm} \) (equivalent to \( \lambda/4 \) at 633 nm) over the central 80% of the coupon. These test coupons should be prepared and separately-delivered to LLNL as soon as feasible following the award of the contract, to expedite qualification of the reflective coating deposition process. Also note the packaging requirements outlined in Section 2.3.5.1.

3.4.2 Silicon Mirror Substrate for Handling and Mounting Procedures:

Vendor shall provide one, complete single-crystal silicon mirror substrate, for verification of the LLNL mirror handling and mounting procedures. This substrate should be prepared in the same manner as the primary mirror substrates. It should be cut to size, ground, prepared with the mounting holes and grooves, and wet-chemical etched with the other substrates. However, only relaxed specifications for figuring and polishing are required for the optical surface: A peak-valley surface height error of \( \leq 158 \text{ nm} \) (equivalent to \( \lambda/4 \) at 633 nm) is required over clear aperture Zone 2, after subtraction of best-fit cylinder reference surfaces (see Sections 2.2.2.1, 2.2.2.2 and Figure 2) with a mid-spatial and high-spatial roughness of \( \leq 1.0 \text{ nm rms} \) (see Section 2.2.2.3). This test substrate should be separately-delivered to LLNL as soon as feasible, to expedite finalization of the mirror handling and mounting procedures.
Acronyms

AFM: Atomic Force Microscope
FEL: Free Electron Laser
LCLS: Linac Coherent Light Source
rms: Root Mean Square
HOMS: Hard X-ray Offset Mirror System
XTOD: X-Ray Transport Optics and Diagnostics

References

1 Peter Stefan, Michael Pivovaroff, Jacek Krzywinski, "Physics Requirements for the XTOD Hard X-Ray Offset Mirror System", PRD 1.5-005-r0

2 LCLS/LLNL Drawing AAA07-502202 "LCLS Facility Optics, HOMS, Hard X-Ray Mirror"
## Appendix A: Mirror Specification Summary

### Mirror General Specifications:

The "LCLS/ LLNL Drawing": AAA07-502202 "LCLS Facility Optics, HOMS, Hard X-Ray Mirror", **includes the following information:**

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror polished shape</td>
<td>Tangential cylinder</td>
<td></td>
</tr>
<tr>
<td>Mirror material</td>
<td>Single-crystal silicon, with a &lt;100&gt; direction oriented along the &quot;Length&quot; of the mirror, as defined in Figure A1, below</td>
<td>No dislocations, cracks, etc. Resistivity ≤ 10 Ω-cm</td>
</tr>
<tr>
<td>Surface finish on non-optical surfaces</td>
<td>Ground and wet-chemical etched</td>
<td>All surfaces of the completed mirror, with the exception of the optical surface, shall be wet-chemical-etched surfaces</td>
</tr>
<tr>
<td>Operating environment and service temperature range</td>
<td>Normal operation in ultrahigh vacuum (UHV) at ~20°C. UHV bake out at 125°C.</td>
<td></td>
</tr>
<tr>
<td>Mirror coating</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>

**Characterization Metrology: within the Clear Aperture Zones (see Figure A2 below)**

### Documentation General Requirements

Include a description of proposed characterization metrology in the "Inspection Test Procedure".

- Supply machine-readable raw data sets for all metrology performed as part of the "Inspection Test Report".
- Data sets shall be in plain ASCII text, or another widely-used format of mutual agreement.
- Describe file format and supply necessary constants and parameters to permit independent data analysis of the raw data.
Figure A1: Pictorial definition of terms

<table>
<thead>
<tr>
<th>Surface Radius</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangential</td>
<td>$150 \text{ km} \leq R_{\text{Tan}} \leq 195 \text{ km}$</td>
</tr>
<tr>
<td>Sagittal</td>
<td>$&gt; 4 \text{ km}$</td>
</tr>
<tr>
<td>Clear Aperture</td>
<td>Figure Error</td>
</tr>
<tr>
<td>----------------</td>
<td>--------------</td>
</tr>
<tr>
<td></td>
<td>Height Error</td>
</tr>
<tr>
<td>Zone 1</td>
<td>Tangential Slope Error</td>
</tr>
<tr>
<td></td>
<td>Sagittal Slope Error</td>
</tr>
<tr>
<td></td>
<td>Height Error</td>
</tr>
<tr>
<td>Zone 2</td>
<td>Tangential Slope Error</td>
</tr>
<tr>
<td></td>
<td>Sagittal Slope Error</td>
</tr>
</tbody>
</table>
### Roughness Specification

<table>
<thead>
<tr>
<th>Roughness</th>
<th>Specification</th>
<th>Measurement Bandwidth</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Spatial</td>
<td>≤ 0.25 nm rms</td>
<td>10^{-3} μm^{-1} to 0.5 μm^{-1}</td>
<td>2 μm to 1 mm</td>
</tr>
<tr>
<td>High-Spatial</td>
<td>≤ 0.4 nm rms</td>
<td>0.5 μm^{-1} to 50 μm^{-1}</td>
<td>20 nm to 2 μm</td>
</tr>
</tbody>
</table>

### Other Requirements:

<table>
<thead>
<tr>
<th>Item</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleaning and Handling</td>
<td>Full, Ultrahigh Vacuum (UHV) practice required. Provide a summary of proposed handling and cleaning procedures in the &quot;Handling and Process Plan&quot;.</td>
</tr>
<tr>
<td>Packaging and Shipping</td>
<td>Vendor shall be responsible for design and fabrication of the mirror shipping container(s). Best protection against contamination and shock/vibration is essential. All-metal, dust-free interior-most enclosure desirable. Include a description of proposed packaging and shipping arrangements in the &quot;Handling and Process Plan&quot;.</td>
</tr>
</tbody>
</table>