Optics Group Strategy Document

Introduction

Achieving the mission of the APS requires high-quality x-ray optics (such as monochromators, mirrors, and focusing optics) to deliver x-ray beams to the samples and, in many cases (such as crystal analyzers), to collect the relevant signal from the experiments. Both the APS-U feature beamlines and the existing APS beamlines require a new generation of x-ray optics that will take advantage of the 100-fold increase in brightness, smaller source size, and increased coherence enabled by APS-U. This document describes the strategy of the APS Optics Group (OPT) to deliver state-of-the-art optics and integrated solutions, in synergy with the other X-ray Science Technologies (XST) groups, to further the missions of the X-ray Science Division (XSD) and the APS.

Mission

The core mission of OPT is to develop and deliver innovative x-ray optics and optical systems and provide related services to further the APS mission of enabling cutting-edge scientific research. In support of this mission, OPT

- Designs, fabricates, and characterizes x-ray optical elements, such as crystal monochromators and analyzers, single- and multi-layer optics, and nano-focusing optics;
- Operates and develops optics fabrication and characterization laboratories and instruments, including the crystal optics fabrication and characterization laboratories, the deposition laboratories, the optical metrology laboratory, and the 1-BM Optics Testing Beamline;
- Conducts R&D to develop future-generation optical components, such as wavefront-preserving optics and wavefront sensors and characterization tools, as well as beamline optics simulation, diagnostics, and optimization tools.

XSD/XST/OPT Organization

Established in the mid-1990s after the commissioning of the APS, OPT has evolved to comprise the following main activities: 1) crystal optics and multilayer optics development and fabrication, 2) zone plate development and fabrication, 3) beamline optics simulation, characterization, and optimization, 4) optical metrology, and 5) operation of the 1-BM Optics Testing Beamline.

Vision

The OPT's vision for the next 5 years and beyond is to be the world-leading expert and knowledge base on wavefront-preserving and nano-focusing x-ray optics R&D, with world-class capabilities, and to continue enabling research in a broad range of high-impact science and technology programs. OPT will also support APS-U beamline optics testing and integration during the dark time and commissioning and post-upgrade operations.

Strategy

OPT performs R&D, design, fabrication, and delivery of cutting-edge optics and related services that aim to further the missions of XSD and the APS and to support the APS-U. These activities are conducted in synergy with other XST support groups and in line with XST and XSD priorities. OPT's strategy is to strengthen its capabilities in the following two key areas:

- **High-performance nano-focusing optics** for current and future APS needs

- **Wavefront-preserving optics and optical systems**, including advanced crystal optics, mirrors, multilayers, and adaptive optics

In developing these capabilities, the OPT group members will 1) develop novel optics tools and techniques (including design, fabrication, and optical and at-wavelength characterizations), wavefront sensors, and relevant simulation codes; 2) perform R&D and design, fabricate, and test optics either independently or in collaboration with beamline scientists or others as appropriate; and 3) collaborate with the XST staff and APS beamline scientists and resident users to ensure successful beamline optics implementation and integration.

Five-year Strategy/Goals

The five-year strategy in the above areas is as follows:
- Develop wavefront-preserving crystal monochromators, multilayers, and mirror optics, including related modeling/simulation and characterization tools; and
- Develop high-resolution focusing optics with the goal of 5 nm for the future APS Ptychoprobe.

Goals and Action Plan for FY 2023

Nano-focusing Optics
- Continue R&D of nano-focusing optics for sub-10-nm spot size focusing needed for APS-U beamlines. Fabricate and test the sub-10 nm spot size focusing optics.
- Continue R&D and fabrication of zone plates for APS beamlines post-APS-Upgrade, including fabricating high-resolution zone plates, optics for new applications, and zone plate-to-beamstop mounting.

Wavefront-preserving Optics and *in situ* Wavefront Sensors
- Continue R&D on advanced wavefront sensing techniques.
- Continue studies of wavefront-preserving high-heat-load mirrors, adaptive mirrors, monochromator crystals, and phase correctors.

Beamline Optics Characterization, Diagnostics, and Optimization
- Continue at-wavelength metrology characterization of X-ray optics (lenses, mirrors, crystals, windows) for APS and APS-U.
- Continue developing beamline wavefront diagnostic tools (complete the protocol for a real-time wavefront sensor using a coded mask and develop advanced nano-focusing measurement techniques) for APS-U beamlines.
- Continue developing AI-based control algorithms integrated with wavefront diagnostic tools for beamline auto-alignment, adaptive optics control, and wavefront and beam focus optimization.

Beamline Optics Simulation and Optimization
- Continue to provide simulation support as part of the optics procurement process for APS-U feature beamlines and the beamlines selected for enhancements.
- Continue to develop and maintain beamline optics design and simulation software and support various optics simulation activities at APS.

Crystal Optics

- Continue to develop, fabricate, and refurbish crystal optics for APS-U and post-APS-U operations in collaboration with APS-U staff beamline scientists and relevant XST support staff.
- Continue to develop capabilities to polish channel-cut Si and Ge crystals. Develop reliable and fast polishing procedures to routinely achieve crystal surface roughness better than 0.5 nm (required by almost all APS-U monochromators).
- Acquire and implement a 2D area detector for the TopoUnit rotating anode system.
- Evaluate the capabilities and performance of crystal fabrication vendors?

Thin-film and Multilayer Optics

- Continue fabrication and refurbishment of high-quality mirrors, coatings, and multilayer optics as needed for APS-U and APS beamlines in collaboration with beamline staff and scientists.
- Operate characterization equipment and continue to enhance characterization capabilities to meet upcoming needs.
- Ashing?

Optics Metrology

- Continue to improve the metrology laboratory instruments and procedures to stay at the forefront and meet the demands of the APS-U beamline mirror measurements.
- Complete the upgrade and commission the metrology laboratory HVAC system.
- Begin measuring APS-U mirrors for quality control and refine and update the APS-U mirror metrology plan as needed, in collaboration with APS-U staff, resident users, and relevant XST staff.

Beamline Operations and Development

- Continue to support 1-BM optics testing activities to the dark period.
- Implement a strategy to upgrade 1-BM for post-APS-U operations, by replacing the monochromator, adding a high-energy monochromator and upgrading equipment.
- Enhance the topography and rocking-curve imaging capabilities to support the APS mission, and meet increasing user demands for the characterization of wide-bandgap semiconductors including SiC, GaN, Ga_2O_3, and others
- Continue to develop and validate tools for testing adaptive optics and related control and automation.

Optics for Future Light Sources

- Continue to develop wavefront-preserving crystal optics (silicon, diamond, etc.), including wavefront-preserving cryo-cooled optics for extreme power loads and advanced imaging optics.
- Continue to develop optical concepts for the cavity-based X-ray free-electron laser oscillator (CBXFELO), output-coupling optics for the CBXFELO, and wavefront-preserving optical components for the CB-XFELO. Design, build, and test a pilot CBXFEL cavity via a DOE-funded CBXFELO collaboration between Argonne and SLAC.
- Continue to develop deformable-mirror-based zoom optics, including *in situ* surface metrology and wavefront sensing with integrated intelligent feedback control.
- Continue to develop new concepts for high-resolution high-throughput x-ray spectrometers (spectrographs, x-ray echo).
- Build a prototype single-shot, high-speed wavefront sensor and test the DOE-funded prototype cryo-mirror developed in collaboration with SLAC, BNL, and ALS.

Strengths, Weaknesses, Opportunities, and Threats (SWOT) Analysis

Strengths	Weaknesses
• Fast response to beamline optics needs and support requests. • Cost-effective and quick delivery of one-of-a-kind optical elements to APS beamlines and users. • Strong and versatile team with a wide range of expertise (unmatched in the U.S.) in optics fabrication, characterization, and theory. • Strong characterization and testing capabilities at 1-BM with unique facilities (e.g. topography). • Access to wide-ranging capabilities within the ANL complex, e.g., CNM. • Established collaborations with APS beamline scientists to advance optics development.	• Obsolete equipment for crystal optics fabrication and characterization limits performance and reduces productivity. • Lack of Central Shops (CS) equipment and expertise for advanced crystal machining, particularly high-precision R&D-grade grinding equipment, results in lower productivity and efficiency. • Reliance on a matrix support system for critical activities leads to lack of project ownership, lack of continuity, and a decreased success rate. • Limited access to advanced micro- and nano-fabrication tools hampers our progress to develop next-generation diffraction-limited nano-focusing diffractive optics.
Opportunities	**Threats**
• Develop new-generation x-ray optics and related expertise and tools. • Strengthen synergies with other XST groups and with beamline scientists in developing and implementing complex optical systems. • Increase scientific and publication output. • Become a world leader in nano-focusing and wavefront-preserving x-ray optics. • Develop strong collaborations within DOE light sources and with industry to help meet APS optics needs.	• Potential for shrinking budgets could impede progress and diminish quality of scientific output. • Reduced investments in staff could compromise readiness for the next shift in x-ray optics technology and will minimize the ability to meet key optics goals for APS Feature beamlines and APS beamline and future DOE light sources. • Moving to a “cost recovery” operating model will significantly diminish much-needed R&D. • Lack of a reliable source of large-size, defect- free crystal materials, including diamond, quartz, sapphire, and SiC, could impede progress.