Advanced X-ray Optics Metrology for Nanofocusing and Coherence Preservation

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What is the point of developing new high-brightness light sources if beamline optics won't be available to realize the goals of nanofocusing and coherence preservation? That was one of the questions raised during a workshop at the 2007 ALS Users' Meeting. Organized by Kenneth Goldberg and Valeriy Yashchuk (both of Berkeley Lab) and featuring 11 invited talks, the workshop brought together industry representatives and researchers from Japan, Europe, and the US to discuss the state of the art and outline the optics requirements of new light sources. Many of the presentations are viewable online at *http://goldberg.lbl.gov/Metrology Workshop07*.

Many speakers shared the same view of one of the most significant challenges facing the development of new high-brightness third- and fourth-generation X-ray, soft X-ray, and EUV light sources: these sources place extremely high demands on the surface quality of beamline optics. In many cases, the 1–2-nm surface error specs that define the outer bounds of "diffraction-limited" quality are beyond the reach of leading facilities and optics vendors. To focus light to 50-nm focal spots, or smaller, from reflective optics and to preserve the high coherent flux that new sources make possible, the optical surface quality and alignment tolerances must be measured in nanometers and nanoradians. Without a significant, well-supported research effort, including the development of new metrology techniques for use both on and off the beamline, these goals will likely not be met. The scant attention this issue has garnered is evident in the stretched budgets and limited manpower currently dedicated to metrology. With many of the world's leading groups represented at the workshop, it became clear that Japan and Europe are several steps ahead of the US in this critical area.

But the situation isn't all dire: several leading groups are blazing a trail forward, and recognition of this issue is increasing. Showing how to build support for this research, Howard Padmore (ALS) presented a strategy based on recent successful efforts to establish a new program in advanced detectors within the U.S. DOE.

The gap between the current state of the art and new beamline optics requirements was one of the main issues raised by Peter Takacs (Brookaven National Laboratory). Along with several other speakers, Takacs showed that for X-ray wavelengths, a mirror figure error of 0.5 nm rms decreases the Strehl ratio noticeably, a 1.0-nm error reduces it to half, and a 2.0-nm error can destroy focusing entirely. Takacs then placed this field in context with a very interesting historical overview, going back to the seminal work of Mori in Japan (1965), through the EUV lithography programs of the 1980s and 1990s, to the current efforts in Japan and Europe.

SLAC's John Arthur contributed a review of the generation mechanisms of synchrotron and free-electron laser (FEL) light and explained design aspects of Stanford's LCLS.

Kazuto Yamauchi (Osaka University, Japan) described his team's world-leading efforts in hard X-ray nanofocusing. They have demonstrated excellent correspondence between externally measured surface figure errors and X-ray focusing performance using a lateral and longitudinal scanning slit and a phase-retrieval algorithm.

Several speakers also addressed advanced instrumentation and scientific motivations behind the drive toward high coherence and nanofocusing.

Frank Siewert (BESSY) described what it took to achieve 0.05-µrad accuracy in his group's state-of-the-art Nanometer Optic component measuring Machine (NOM), recently used in cross-correlation experiments with numerous other slope-measuring instruments worldwide and in collaborative work on the Nanometer Optics Components program in Europe.

Applications of visible-light Shack-Hartmann wavefront sensing to two-dimensional long-trace profiler (LTP) measurements both on and off the beamline were shown by François Polack (SOLEIL). Polack also described the MARX project at SOLEIL, which is creating active mirror elements and at-wavelength testing for micro- and nanofocusing.

Tetsuya Ishikawa (SPring-8) described the development of advanced optical systems for synchrotrons and FELs, including a Hambury-Brown Twiss interferometer for coherence measurements. He also showed the importance of using beryllium windows of exceptional quality to avoid coherent speckle artifacts downstream.

Ali Khounsary (APS) showed advanced mirror polishing and K-B bending that allowed his group to achieve 100-nm focusing. He reminded the audience that reaching 0.1–0.2-µrad surface quality requires measurement accuracy levels that are higher still. Khounsary revealed plans for a hard X-ray Laue lens geometry that may reach 16-nm focal spot size.

The instrumentation requirements for several Fermi and Elettra FEL endstations were discussed by Daniele Cocco (Elettra). To meet the stringent mirror shape requirements of these microscopy and scattering beamlines, his group is developing active K-B mirrors with multiple piezoelectric actuators to control the mid and low spatial frequency figure.

Yi-De Chuang (Berkeley Lab) described many applications in the science of complex materials that can be greatly advanced with 1-meV energy resolution and tightly focused beams. High-temperature superconductivity, colossal magnetoresistance, gigantic thermal power, and anomalous magneto-optical properties are just a few of the topics that will be studied by the new MERLIN beamline under development at the ALS.

Finally, Regina Soufli (Lawrence Livermore National Laboratory) described optical requirements for both hard and soft X-ray mirrors in the LCLS, where power levels will be orders of magnitude higher than third-generation synchrotron sources. Consequently, the melting temperatures of coating materials must be carefully considered. Coupled with reflectivity requirements, four candidate materials have emerged: Si, SiC, B_4C, and Be. Soufli showed the results of extensive surface characterization of vendor sample mirrors, with two vendors having the potential to meet LCLS specs.

A lively discussion led by Goldberg and Yashchuk continued long after the formal talks. What was clear to all is that despite the unavoidable fact that sub-2.0-nm rms quality is required for these new sources to reach their design potential, there is no substantive plan within the US to create or support the development of these mirrors. Without improved LTP accuracy and a state-of-the-art at-wavelength on-beamline testing capability, the creation of these mirrors, as Takacs wryly noted, is an issue being left to *magic*. With or without supernatural intervention, *InSync*'s Jim Metz notably offered to fabricate optics to any of the specifications discussed, *provided that metrology becomes available.* This begs a twist on the old adage (attributed to Lawrence Livermore National Laboratory's Norm Brown): "If you can't measure it, I can make it." ■

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Theory at the ALS

As a result of advances in instrumentation at DOE-supported synchrotron radiation facilities, tremendous amounts of spectroscopic data are becoming available on wide classes of material systems. Theoretical modeling is crucially important for interpreting spectroscopic data and for developing viable physical models of novel materials and phenomena and exotic states of matter. In light of the need of theory for experimental sciences, a joint workshop between the ALS and SSRL was held during the ALS Users' Meeting on Saturday, October 6, 2007. The workshop was separated into two parts—Part I: Computation and Spectroscopy and Part II: Present/Future of Strongly Correlated Condensed Matter Physics.

Part I: Computation and Spectroscopy. In this morning session there were a total of four presentations. Arun Bansil from Northeastern University highlighted the role of parallel theoretical modeling and the opportunities so opened up in connection with present-day high-throughput, high-resolution work at various user facilities. Tom Devereaux from Stanford University described the opportunities that exist for studying mid- to low-energy excitation with the use of inelastic X-ray scattering. Steve Louie from UC Berkeley explained electronic and optical excitations in nanostructures. The last talk of the session was by David Prendergast from the Molecular Foundry, who presented a simulation of X-ray absorption near-edge spectroscopy analysis of aqueous systems.

Part II: Present/Future of Strongly Correlated Condensed Matter Physics. The afternoon session focused on the present and future of strongly correlated condensed matter physics. This session also had a total of four talks on cuprates, manganites, and some discussion of future new directions. From all the presentations, it was pointed out that Landau's paradigm (namely the order parameter and Fermi liquid theory), which was the foundation for condensed matter physics in the past, is not adequate for understanding the properties of many strongly correlated electronic systems. In his talk, Patrick Lee from MIT took the audience from high Tc to quantum-spin liquid and back. Steve Kivelson from Stanford University explained the optimal inhomogeneity for high-temperature superconductivity. Ashwin Wishwanath and Dunghai Lee from UC Berkeley explained the physics beyond Landau, pointing out novel phases and spin-charge separation in correlated quantum matter.

The final concluding session turned out to be very lively and provided guidance for future plans. The general feeling was that, although DOE expenditures on the operational costs of synchrotrons and FEL facilities in the Bay Area at the ALS, SSRL, and LCLS are estimated to amount to about $200 million annually, there is little that has been developed by way of a dedicated theoretical effort to support this considerable investment. It was decided by the participants to write a white paper describing why the need for theoretical support is critical and urgent and outlining an action plan to begin a serious targeted effort for developing a robust theoretical infrastructure in support of these facilities.

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