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International Workshop on Science with Coherent X-rays

An International Workshop on X-ray Science with Coherent Radiation was held in Berkeley, California, August 22-23, 2003. This Workshop was set up as the only Satellite Meeting to the 2003 International Conference on Synchrotron Radiation Instrumentation. It was co-chaired by Qun Shen (CHESS), John Spence (Arizona State/LBNL), and John Arthur (SSRL), with financial support provided by Cornell High Energy Synchrotron Source (CHESS), Advanced Light Source (ALS), and Advanced Photon Source (APS). More than 120 scientists, from 14 countries, attended the Workshop, about twice as many as expected, making it one of several exciting and memorable conferences in x-ray science for the summer of 2003.

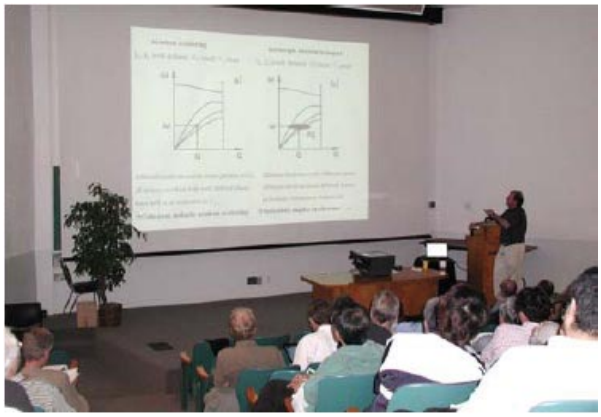
The theme of the Workshop was focused on two closely related questions. First, with new coherent x-ray sources such as Energy Recovery Linac (ERL) and X-ray Free Electron Lasers (XFEL) on the horizon, what new types of x-ray science and experiments can be performed? Second, what technical issues on x-ray optics, methods, algorithms, etc., have to be resolved in order to perform the new types of x-ray science at the future sources? The attendees enthusiastically participated in the discussions of the above two questions through 23 invited talks by the leading experts in the field, and 16 poster presentations as well as informal conversations in small groups at the Workshop.

From left: Christian David (PSI), Gerhard Grubel (ESRF), and Sunil Sinha (UCSD) enjoy a much needed break at the Workshop.

The Workshop started on Friday morning with a brief welcome and introduction by Qun Shen (CHESS), followed by two short oral presentations on coherence properties of ERL sources by Sol Gruner (Cornell) and on XFEL properties by Jerry Hastings (SSRL). Bruno Lengeler (Aachen) then gave a 50-minute tutorial on coherence in x-ray physics, which many participants thought was very comprehensive and helpful in understanding the various concepts on coherent x-rays. This first session on new sources and tutorial was chaired by Janos Kirz (SUNY Stony Brook).

Sunil Sinha (UC San Diego) chaired the next session on Friday morning on x-ray intensity fluctuation spectroscopy, or x-ray speckle experiments. The discussion started with an overview talk by Mark Sutton (McGill), followed by more detailed experimental examples on structure and dynamics of complex fluids given by Gerhard Grübel (ESRF) and on magnetic domains using resonant soft x-ray scattering given by Jereon Goedkoop (Amsterdam). While fast dynamics on sub-μs scales are routinely observed for complex fluids and polymer samples, speckle experiments on magnetic specimens are more difficult and the current interest in this area has been on real-space reconstruction

and on speckle metrology. Looking ahead, Goedkoop concluded that future applications may include 'slow' dynamic studies on time scales of 0.01-100ms with magnetic x-ray intensity fluctuation spectroscopy and 'fast' studies on 1 ns scales with magnetic pump-probe experiments.



Bruno Lengeler (Aachen) gives his tutorial lecture on x-ray coherence.

The topic of coherent diffraction imaging of nanocrystalline and noncrystalline specimens was covered in two sessions, one chaired by Steve Wilkins (CSIRO) on Friday afternoon and the other by John Spence (Arizona State) on Saturday afternoon. Ian Robinson (Urbana-Champaign) introduced the topic from the traditional point of view of scattering and diffraction and used several intuitive examples to explain the concept of coherent x-ray diffraction and the oversampling phasing technique. John Spence continued the discussion from a coherent electron diffraction background and introduced a related concept of ptychography on periodic objects, namely, using overlapping coherent diffraction peaks in reciprocal space to obtain interference and thus phase information. The discussion continued Saturday afternoon with David Sayre (SUNY Stony Brook), who summarized in his unique and captivating presentation style the pioneering and present work by the Stony Brook team in diffraction imaging of a general particle. John Miao (SSRL) provided further theoretical explanation of the oversampling phasing method, and added many recent highlights in this area, one being the diffraction imaging of *E. Coli* bacteria using coherent x-rays.

The last two talks in Saturday afternoon's session touched upon the important radiation damage issue in coherent diffraction imaging. Malcolm Howells (ALS) reported that the combined effect of (a) dose requirement for a given resolution, which scales inversely as the fourth power of resolution, and (b) dose limit due to radiation damage, leads to the conclusion that 10nm resolution should be possible for imaging life science specimens and 2nm for more radiation resistant samples in materials science. Stefan Hau-Riege (LLNL) presented a hydrodynamic model for investigation of deterioration of a macromolecule caused by x-ray irradiation, from which an optimal resolution as a function of x-ray pulse and molecule parameters is obtained considering both radiation damage and image classification. The results showed a pulse length of <4fs is needed for achieving atomic resolution in single molecule diffraction imaging using an XFEL source.

The session on x-ray optics for coherence applications on Friday afternoon, chaired by Don Bilderback (CHESS), started with a talk on coherence-preserving reflecting and crystal optics by Tetsuya Ishikawa (SPring8), who reported a whole range of state-of-the-art fabrication, polishing, and metrology results on x-ray mirrors and crystals with figure errors on x-ray mirrors controlled to <1nm and slope errors to <0.1μrad. These advances have led to a near diffraction-limited Kirkpatrick-Baez mirror system that focuses 15 keV x-rays to a 180nm by 90nm spot at SPring8 1km beamline. The second talk in the session was given by Stefano Cabrini (ELETTRA), on the topic of shaping x-rays with diffractive coded nano-optics, where the idea of using coherent x-ray diffraction to 'convert' something like a diffraction pattern back to a real space image was presented. David Paterson (APS) followed with a talk on x-ray coherence measurements using a complex diffractive mask called a uniformly redundant array to achieve a complete measurement of the entire transverse coherence function. In the last talk of the session, Wenbing Yun (Xradia, Inc.) gave an overview of current status of zone plate fabrication with a 60nm resolution in the hard x-ray regime, and reported some impressive microscopy and 3D tomographic studies of semiconductor devices using a laboratory-based x-ray microscope.

Standing and debating (from left): Bruno Lengeler (Aachen), Friso van der Veen (PSI), Wenbing Yun (Xradia), and Don Bilderback (Cornell) during the lunch hour discussion Saturday.

In a lunch-hour discussion session on optics, organized by Don Bilderback (CHESS) and held on Saturday, Friso van der Veen (PSI) presented his recent result that there appears to be a fundamental limit of ~10nm on all reflecting optics based on wave propagation theory. The question whether this may be a basic fundamental limit for all x-ray optics generated much debate among workshop participants, with no conclusion reached by the end of the short lunch hour period.

The sessions on x-ray microscopy, holography and interferometry were held on Saturday morning, chaired by Ian McNulty (APS) and Tetsuya Ishikawa (SPring8) respectively. In the first talk of the morning, Chris Jacobsen (SUNY Stony Brook) gave an overview on coherence and x-ray microscopy. He stressed that while coherence makes x-ray optics such as zone plates perform better, not all forms of microscopy require coherence per se. He then gave many examples of x-ray microscopy applications including phase contrast imaging in STXM and some recent radiation damage studies showing cryo-temperature protects sample against mass loss but not against breaking of atomic bonds. The topic of recovering phase and correlations in coherent x-ray wavefields was covered by two talks given by Keith Nugent and Andrew Peele, both from University of Melbourne. Nugent gave a beautiful illustration on the propagation-based phase retrieval algorithm, by using his pair of glasses (specimen) and looking at how the image would vary on the projector screen when the specimen-to-screen distance is changed. Peele reported in his talk that x-ray vortices produced by 'singular optics' may play an important role in propagation-based phase recovery. In the same session, Peter Cloetens (ESRF) gave an overview on 3D phase tomography using hard coherent x-rays. He provided many recent examples ranging from evolution of liquid foams and solidification of binary alloys to breast biopsy and imaging of cells. For this type of in-line 3D imaging, an undulator source that can provide both spatial and sufficient temporal coherence is preferred with no x-ray optics, because everything in the beam can act like a phase object!

Bernard Adams (APS, right) talks with Andrew Peel (Melbourne) after Andrew's talk, while Tetsuya Ishikawa (SPring8) prepares for next session.

From left: Katharina Luning (SSRL), Jerry Hastings (SSRL), John Arthur (SSRL), and Edgar Weckert (HASYLAB) enjoy a chat in front of the posters.

After a short coffee break, Christian David (PSI) started the session on holography and interferometry with a talk on diffractive optics and shearing interferometry, in which he presented the recent results using a lithographically fabricated beam splitter (grating) to perform differential phase contrast imaging of various phase objects. The second talk of the session, given by Michael Drakopoulos (ESRF), illustrated how high-quality imaging x-ray optics, a compound refractive lens in this case, coupled with sufficient transverse coherence, can be used to image a 2D diffraction pattern, much like the case of electron microscopy. The final talk in this session was given by Makina Yabashi (SPring8), who presented the latest results obtained at SPring8 on two-photon intensity interferometry, where both spatial and temporal coherence were required and realized by high-resolution crystal optics.

The wide range of topics covered in this Workshop were concisely and well summarized by John Arthur (SSRL) in 15 minutes as the last formal presentation of the Workshop. He concluded with some final thoughts that (a) use of coherent x-rays has transmogrified from an art into a science, (b) interest in the use of coherence is exploding, and (c) the future looks bright.

Interesting and timely topics, high-quality presentations, and high concentration of leading scientists in x-ray coherence field were not the only reasons why the Workshop was so enjoyable to many participants. Friendly and skillful administrative staff, as well as beautiful weather in the Berkeley area, were among the other reasons. In addition, to many the Workshop marked the beginning of an intriguing trend in synchrotron x-ray science today, which is the merging of two traditionally separate scientific groups, x-ray imaging and x-ray scattering, due to the increasingly available coherence in today's x-ray sources as well as the prospect of future coherent sources such as ERL and XFEL. Thus to many participants, this Workshop showed many opportunities, and a truly bright future in scientific applications of coherent x-rays.

All Workshop presentations and discussion materials have been posted at the CHESS website http://www.chess.cornell.edu/Meetings.

Administrative helpers (from left): Cathy Cooper (ALS), Virginia Bizzell (CHESS), and Linda Senft (ALS) are happy that the meeting is finally over!