X-ray Microscopy 2002
July 29 – August 2, 2002, Grenoble, France
Main Organizer: Jean Susini (ESRF)

- Oral & poster presentations
- 239 registrants
- 49 PhDs
- Visit to ESRF
- Dinner at Chateau d’Herbelon

Highlights of XRM'02
- Novel optics
- Phase contrast
- More hard x-rays
- Lots of applications …
Monday July 29, 2002

09:00 – 09:30 Welcome by W. Stirling (ESRF Director General)

SESSION I: Instrumentation
Chair J. Kirz, State University of New York, Stony Brook, USA

09:30 – 10:00 H. Ade, North Carolina State University, USA
Bending magnet STXM at the ALS

10:00 – 10:30 P. Guttmann, Universität Göttingen, Germany
The transmission X-ray microscope at BESSY II

10:30 – 11:00 Coffee break

11:00 – 11:30 Y. Suzuki, SPring-8 Facility, Japan
Hard X-ray Microscopy Activities at SPring-8

11:30 – 12:00 A. Simionovic, ESRF, France
X-ray microscopy and nano-analysis activities at the ESRF

12:00 – 12:30 P. Moretto, Université de Bordeaux I, France
The nuclear microprobe as a complementary technique to X-ray microscopy

12:30 – 14:00 Lunch

SESSION II: Instrumentation (cont.)
Chair C. Kunz, ESRF, Grenoble, France

14:00 – 14:20 B. Lengeler, Aachen University of Technology, Germany
Beryllium parabolic refractive X-ray lenses for full field imaging and scanning microscopy with hard X-rays

14:20 – 14:40 L. McNulty, Argonne National Laboratory, USA
The 2D-B Intermediate-energy Scanning X-ray Microscope at the APS

14:40 – 15:00 V.V. Aristov, Institute of Microelectronics Technology RAS, Russia
Modern status of X-ray optics development in IMT RAS

15:00 – 15:20 Y. Wang, Xradia, USA
A laboratory source based hard-x-ray microscope for 3D imaging of Ics

15:20 – 15:40 Q. Shen, Cornell High Energy Synchrotron Source, USA
Coherent X-ray Imaging and Microscopy Opportunities Using a Diffraction-Limited Energy Recovery Linac (ERL) Synchrotron Source

15:40 – 16:00 Y. Kagoshima, Himeji Institute of Technology, Japan
Hard X-ray Phase-Contrast Microscope for Observing Transparent Specimens

16:00 – 18:00 Refreshments and Poster Session (Instrumentation)

Tuesday July 30, 2002

SESSION III: Instrumentation (cont.)
Chair D. Joyce, Charles Fabry Laboratory, Institut d’Optique, France

09:00 – 09:30 H. Hertz, Royal Institute of Technology/ESRF, Sweden
Table-Top X-Ray Microscopy: Sources, Optics and Applications

09:30 – 10:00 C. David, Paul Scherrer Institute, Switzerland
Diffractive Soft and Hard X-ray optics

10:00 – 10:30 Th. Schmidt, Bessy II/Berlin Wörzberg University, Germany
SMART – a multimethod spectromicroscope: advantages and first results

10:30 – 11:00 Coffee break

SESSION IV: Applications
Chair H. Kihara, Kansai Medical University, Japan

11:00 – 11:30 A.P. Hitchcock, McMaster University, Canada
Soft X-ray spectro-microscopy of polymers

11:30 – 12:00 J. Maser, Argonne National Laboratory, USA
Trace metals and their relation to bacterial infections studied by X-ray microscopy

Wednesday July 31, 2002

SESSION V: Applications (cont.)
Chair D. Raoux, SOLEIL, Orsay, France

09:00 – 09:30 M. Kiskinova, Elettra Synchrotron Light Source, Italy
Morphology, chemistry, electronic and magnetic properties of interfaces probed with submicron spatial resolution using X-ray photoelectron microscopy

09:30 – 10:00 P. Evans, Bell Laboratories, USA
Spin density wave domains in chromium

10:00 – 10:30 P. Fischer, Max-Planck-Institute, Germany
Magnetic imaging with soft X-ray microscopy

10:30 – 11:00 Coffee break

11:00 – 11:30 H. Ohldag, Stanford Synchrotron Radiation Laboratory c/o ALS, USA
Spectromicroscopy of Magnetic Interfaces using XPEEM

11:30 – 12:00 G. Mitchell, Dow Chemical Company, USA
Polymers characterization by X-ray spectro-microscopy

12:00 – 12:30 C.A. Larabell, University of California, USA
Imaging Cells: Live-Cell Light and High-Resolution Soft X-ray Microscopy
Thursday August 1, 2002

SESSION VIII: Applications (cont.)
Chair C Jacobsen, State University of New York, Stony Brook, USA

09:00 – 09:30 J. Thieme, Universität Göttingen, Germany
X-ray spectromicroscopy in environmental sciences

09:30 – 10:00 G. J. Flynn, SUNY-Plattsburgh, USA
Interplanetary Dust Particles and micrometeorites by soft and hard X-ray microscopy

10:00 – 10:30 P. Philippot, IPGP Université Paris-Jussieu, France
High resolution chemical imaging of biogeochemical markers in hydrothermal systems

10:30 – 11:00 Coffee break

SESSION IX: Methods and Novel Approaches
Chair G.R. Morrison, Department of Physics, King's College London, UK

11:00 – 11:30 M. Feser, Stony Brook University, USA
Segmented detector for phase contrast scanning microscopy

11:30 – 12:00 T. Wilhelm, RheinAhrCampus Remagen, Germany
Differential Interference Contrast X-ray Microscopy with zone plate doublets at ESRF beamline ID21

12:00 – 12:30 S. Vogt, Argonne National Laboratory, USA
Application of Principal Component Analysis to X-ray Fluorescence Imaging

12:30 – 14:00 Lunch

SESSION X: Methods and Novel Approaches (cont.)
Chair S. Aoki, Institute of Applied Physics, University of Tsukuba, Japan

14:00 – 14:20 C. Jacobsen, Stony Brook University, USA
Analysis of soft x-ray spectrum images based on principal components and clusters

14:20 – 14:40 T. Salditt, Universität Saarbrücken, Germany
1D and 2D x-ray waveguides: optics, nanobeam production, and field-enhancement

14:40 – 15:00 S.C. Mayo, CSIRO Manufacturing Science & Technology, Australia
Applications of Phase-Contrast X-ray Microscopy in an SEM

15:00 – 15:20 G.R. Morrison, King's College, London, UK
STXM Imaging with a Configured Detector

15:20 – 15:40 E.M. Lauridsen, Center for Fundamental Research, Denmark
The 3-Dimensional X-Ray Diffraction Microscope: 3D Maps of Grains and Grain Dynamics in Polycrystalline Materials

15:40 – 17:30 Refreshments and Poster Session (Methods and Novel Approaches)

17:45 – 23:30 Conference dinner

Friday August 2, 2002

SESSION XI: Methods and Novel Approaches (cont.)
Chair I. McNulty, Advanced Photon Source, Chicago, USA

09:00 – 09:30 G. Schneider, Lawrence Berkeley National Laboratory, USA
High resolution X-ray tomography with applications in biology and materials science

09:30 – 10:00 N. Watanabe, University of Tsukuba, Japan
Optical holography in the hard X-ray domain

10:00 – 10:30 P. Cloetens, ESRF, Grenoble, France
High resolution holotomography

10:30 – 11:00 Coffee break

11:00 – 11:30 E. Di Fabrizio, Elettra Synchrotron Light Source, Italy
Design and fabrication of new optics for X-ray microscopy and material science

11:30 – 11:50 M. Chukalina, Institute of Microelectronics Technology RAS, Russia
X-ray Fluorescence Tomography for non-destructive semi-quantitative study of microobjects

11:50 – 12:10 J. Miao, Stanford Synchrotron Radiation Laboratory, USA
High Resolution 3D X-ray Diffraction Microscopy and Its Potential of Imaging Single Biomolecules

12:10 – 12:30 M. Howells, Lawrence Berkeley National Laboratory, USA
X-ray microscopy by phase-retrieval methods at The Advanced Light Source

12:30 – 14:00 Lunch

SESSION XII: Methods and Novel Approaches (cont.)
Chair A. Michette, Department of Physics, King's College London, UK

14:00 – 14:30 Werner Meyer-Ilse Award (chair: A. Michette)

14:30 – 14:50 I. Koyama, The University of Tokyo, Japan
Phase-Contrast X-ray Imaging with a triple Bragg-case Interferometer

14:50 – 15:10 U. Neubäumer, ESRF, Grenoble, France
Phase contrast X-ray microscopy at 4 keV photon energy with 60 nm resolution

15:30 – 15:50 Y. Kohmura, SPRing-8, Japan
Phase retrieval with two beam X-ray interferometer

16:00 – 16:30 Closing remarks by G. Schmahl, Universität Göttingen, Germany

16:30 – 17:00 Refreshments

Shen 8/30/2002
Background on X-ray Microscopy

**ESRF ID21: TXM** 3-6 keV

**ESRF ID21: SXM** 2-10 keV & < 2keV

- Two types: full field & scanning
- All types of materials are studied, from biological to magnetic
- Increasing number of SR imaging microscopes worldwide due to availability of
  => high-resolution lens-like optics: zone plates, KB mirrors, CRLs
  => high-brilliance synchrotron sources

⇒ transmission
⇒ fluorescence
⇒ XPEEM
Nanofabricated Diffractive Optics

Linear zone plates:  C. David (PSI)

Multilevel zone plates:  Fabrizio (Elettra) & David (PSI)

Complex zone plates:  Di Fabrizio (Elettra)
Wilhein (Remagen, Germany)

Photon sieves:  P. Charalambous (King’s College)

1D & 2D wave guides:  T. Salditt (U. Saarbrucken)

Diamond refractive lenses:  A. Freund (ESRF)

68.7nm x 33.0nm (derived)
**Linear zone plates:**

C. David (PSI)

⇒ Matching anisotropic source shape & size

⇒ Tilted to increase ZP's efficiency
Multilevel Zone Plates:

C. David (PSI)

Photon Sieves:

P. Charalambous (King’s College)

L. Kipp et al., Nature (2001)
Complex zone plates: Di Fabrizio (Elettra) Wilhein (Remagen, Germany)

⇒ Multiple focal spots in single or multiple focal plane for differential interference contrast microscopy
⇒ Complete beam shaping for maskless lithography & x-ray induced CVD
Differential Interference Phase Contrast with ZP Doublet

Wilhein et al. APL 78, 2082 (2001).
ESRF, ID21, 4 keV

PMMA 2µm-thick: 98.7% transmission

Giant moss spores of *Dawsonia superba*
X-ray Shearing Interferometer:
C. David (PSI)

Si phase grating beam splitter

Experiment
polystyrene spheres of 0.1mm and 0.2mm

Calculation
Some Examples on Applications

Nano-tomography on AMD K6: C.G. Schroer (Aachen)  
A. Snigirev (ESRF)

Magnetic imaging with XMCD: P. Fischer (MPI, Stuttgart)  
G. Denbeaux (ALS)

3D XRD mapping of grains: H. Poulsen (Riso)  
B. Larson (ORNL) @ IUCr

Element mapping in biological samples: C.G. Schroer (Aachen)  
A. Snigirev (ESRF)

Spectromicroscopy of polymers: A.P. Hitchcock (McMaster)

Cryo tomography soft x-rays: C.A. Larabell (Anatomy, UCSF)

Many many more ……

Yeast: single celled eukaryotic organism, ~5µm in diameter
Nano-tomography on AMD K6:

C.G. Schroer (Aachen)
A. Snigirev (ESRF)

ID22 ESRF:
parabolic Al refractive lens imaging onto 2D detector
x-ray energy 25 keV
magnification 20.9x
3D resolution 410nm
Fluorescence Microtomography with Micro-beam:

C.G. Schroer (Aachen)
A. Snigirev (ESRF)

ID22 ESRF:
parabolic Al refractive lens
focal spot: 3 µm x 0.9 µm
scan step: 1 µm
132 projections in 360°

Specimen:
mycorrhizal root of tomato plant, grown on heavy metal polluted soil
Full Field Fluorescence Microscope

Ohigashi, Watanabe, Yokosuka & Aoki, JSR 9, 128 (2002).

1Kx1K CCD: 12µm x 12µm pixels, photon counting => 210eV @8keV

10:1 magnification
Pt-coated Pyrex
Full field magnetic imaging with XMCD:

P. Fischer, G. Schutz (MPI, Stuttgart)
G. Denbeaux, D. Attwood (ALS)
⇒ No polarity switching necessary
⇒ Contrast reversal between L3 & L2
⇒ Compared to EM: no effects from applied $H$

Fe $L_3$ & $L_2$

Fe $4A$ / Gd $4A$ x75

Fig. 2. Images of magnetization within an iron gadolinium multilayer, imaged at the iron $L_{III}$ (a) and $L_{II}$ (b) edges (707.5 and 720.5 eV, respectively). The expected contrast reversal of X-MCD between the edges can be seen.
Figure 3. A sequence of magnetic images at the Fe L₃ edge of the layered Gd–Fe system in a varying applied magnetic field covering the complete hysteresis loop. The different stages saturation (S), nucleation (N) and worm-like domains (W) are marked. The hysteresis loop ($M/M_s$ versus $H$ (kOe)) (—) was determined from MOKE measurements.
Magnetic Nanostructures


Fig. 2a,b. Remanent domain pattern in an array of square FeGd dots with an edge length of 670 nm a in the “as-grown” state and b after saturating and demagnetizing the sample.
Fig. 1. MTXM image of magnetic domains in circular dots with a diameter of 190 nm and in a continuous part of a multilayered FeGd system.

Fig. 4. MTXM images taken at the $L_3$ and $L_2$ edges of a Cr(3 nm)/Fe(50 nm)/Cr(6 nm) system.
Imaging Magnetic ‘Bits’ in Magneto-optical Film

Fischer et al. JSR (2001)

Fig. 1 M-TXM images taken at the Fe L₃ edge of a SiN(70nm)/Tb₂₅(Fe₇₅Co₂₅)₇₅(50nm)/SiN(20nm) maneto-optical film. Left: Recorded pattern in a low $H_c$ systems with low laser power. Right: Corresponding pattern in a high $H_c$ systems with high laser power. The scalebar is 1μm.

Thermomagnetic recording by laser-pumped magnetic field modulation
Undulation Instability in Magnetic Nanowires

Eimuller et al. JAP (2002)

Multilayer:
(4Å Fe/4Å Gd)x75 on 300Å Si₃N₄
8nm Al cap layer

E-beam lithography:
2μm to 100nm lines

FIG. 1. Undulation instability in nanowires of 670 nm width. With decreasing magnetic field, straight stripe domains, visible as dark and light zones in both strips (a) accumulate strain and undergo a buckling instability. Thereby the “dark” stripe breaks open [marked in (b)] and forms a wavelike pattern (c), which transforms into a rectangular modulation in (d).
FIG. 5. The undulation period $\Lambda_0$ depends linearly on the width of the strips, $L_z$. A linear least squares fit of the data (upper line) shows exactly the slope of the function predicted by theory for extended systems (lower line).
Spin dynamics on nanostructured magnets with pump-probe

*Deneaux et al. XRM (2002)*

⇒ micro-coil with pulser (rise time ~100ps)

⇒ x-ray pulse from ALS (Fwhm<70ps, 3MHz)

⇒ pump-probe delay (0 < $\Delta t$ < 328ns)
Highlights on Phase Contrast

Zernike phase contrast: Y. Kagoshima (Spring-8)
U. Neuhausler (ESRF)

Phase contrast in STXM: M. Feser (SUNY-SB)
G. Morrison (Kings College)

Differential phase contrast: T. Wilhein (U. Koblenz, Germany)

Phase contrast tomography: P. Cloetens, J. Baruchel (ESRF)

Shearing interferometry: C. David (PSI)

Diffraction microscopy: J. Miao (SSRL)
M. Howells (LBNL)
J. Kirz & D. Sayre (SUNY-SB)

Nanocrystal diffraction imaging: I. Robinson (UIUC) @ IUCr
Absorption Contrast vs. Phase Contrast

- Phase contrast is $10^4$ higher than absorption contrast for protein in water @ 8keV
- Dose reduced to level comparable to using water-window in soft x-ray region

Refraction index: $n = 1 - \delta - i\beta$

Absorption contrast: $\mu z = 4\pi\beta z/\lambda \sim \lambda^3$

Phase contrast: $\phi(z) = 2\pi\delta z/\lambda \sim \lambda$

Kirz (1995): 0.05µm protein in 10µm thick ice

Kagoshima et al. (2001): protein $C_{94}H_{139}N_{24}O_{31}S$

$\rho = 1.35g/cm^3$, $t = 0.1\mu m$ in 10µm water
**Principle of Zernike Phase Contrast**  
*(Born & Wolf)*

For pure phase object:  
\[ F(x) = e^{i\phi(x)} \sim 1 + i\phi(x) \]

\[ \Rightarrow \text{No absorption contrast: } |F|^2 \sim 1 \]

**Zernike method** in visible optics:

\[ F'(x) \sim \pm i + i\phi(x) \Rightarrow \text{Phase contrast: } |F'|^2 \sim 1 \pm 2\phi(x) \]
Zernike Phase Contrast

for x-rays

**Soft X-rays**: Schmahl et al. (1995). BESSY, 0.5 keV.

**Hard X-rays**: Kagoshima et al. (2001). SPring8, 10keV.

3-5 minutes exposures at SPring-8 undulator BL24XU

Conidium of Curvularia species
Zernike Phase Contrast


SPring-8 BL24XU

Cu mesh

Polystyrene spheres $D=7\mu m$
Phase Contrast in STXM


M. Feser: recipient of Meyer-Ilse Award on XRM (2002).

$\Rightarrow$ Multi-segment detector
Silicon Multi-channel Integrating Detector With Segmentation

In collaboration with P. Rehak, G. DeGeronimo (Instrumentation Division, Brookhaven National Laboratories), L. Strüder, P. Holl (MPI Halbleiterlabor, Germany)

- 7 Segments that are matched to the scanning transmission x-ray microscope geometry
- Each segment is connected to an independently integrating electronics channel.
- The integration time is variable; gating is provided by the microscope electronics and matched to the pixel dwell time.
Flexible Imaging configurations

- Bright field (partially coherent absorption contrast)
- Dark field (coherent scattering)
- Nomarski differential interference contrast
- Differential interference contrast

Phase Contrast in STXM with CCD

G. Morrison (King’s College)

Software-configurable CCD:
- absorption
- phase contrast
- dark field

=> simultaneous detection of both $\delta$ and $\beta$ on the same sample area

Phase contrast modes:
- $1^{st}$ moment $\langle x \rangle = \sum x_i \cdot I(x_i, y_i)$
- $1^{st}$ moment $\langle y \rangle = \sum y_i \cdot I(x_i, y_i)$
- measures phase gradient

TXM and STXM:
- related by optical reciprocity
- detector in STXM $\Leftrightarrow$ extended source in TXM

multi-element

80x80 CCD
3 x-rays/pixel
@ 3keV uncooled
4.4 Conclusion And Outlook

We have demonstrated the usefulness of Fourier filtering techniques developed for STEM in the scanning x-ray microscope if a segmented detector is employed. The reconstruction of a test pattern revealed that the phase image contains more contrast and shows features not visible in the incoherent image and the reconstructed absorption image. It is also seen that the phase image is not affected by fluctuations in the beam intensity, since fluctuations of detector segment signals which are in phase are only transferred to the absorption image.

The test pattern reconstruction and spatial frequency analysis shows that the x-ray microscope operates at the resolution limit of the zone plate optics. Since the microscope did not make use of the pneumatic vibration isolation system for this experiment, we can also conclude that the amplitude of mechanical vibrations in the system is below the resolution limit.

Unfortunately, the X1 undulator beamline at the NSLS delivers just enough coherent x-rays to fulfill the coherence requirements assumed for the derivation of the reconstruction. Relaxation of these requirements will without a doubt decrease the usefulness of this method and we are planning to investigate the

⇒ phase-contrast below C K-edge for biological specimens?
Phase Retrieval in Phase-Contrast Imaging

Phase Retrieval: \( I(u, v) \rightarrow \rho(x, y) = ? \)

**Propagation based method:**

Nugent et al., PRL 77, 2961 (1996)
Paganin & Nugent, PRL 80, 2586 (1998)
Phase is defined by: (i) index of refraction \( n(\mathbf{r}) \)

\[ n = 1 - \delta + i \beta \]

\[ k = n k_0 \]

\[ e^{ikz} \sim k_0 \int n(x,y,z) \, dz \]

(ii) energy flow \( \mathbf{S}(\mathbf{r}) \)

\[ E = E(\mathbf{r}) \, e^{ikr} = E(\mathbf{r}) \, e^{i\phi(\mathbf{r})} \]

\[ \nabla \phi = \nabla (k \cdot \mathbf{r}) \]

\[ = k = \text{propagation direction} \]

Transport of intensity equation

Poynting vector: \( \mathbf{S}(\mathbf{r}) \sim |E|^2 \mathbf{k} \sim I \nabla \phi \)

Energy conservation: \( \nabla \cdot \mathbf{S} = 0 \)

\[ \Rightarrow \nabla \cdot (I \nabla \phi) = 0 \]

Solution of \( \phi \) from intensity \( I(\mathbf{r}) \)
\textbf{Phase Imaging \\ & Tomography}

- A form of \textit{Gabor in-line holography}
- Coherence over 1st Fresnel zone \( (\lambda R)^{1/2} \)
- Image reconstruction (phase retrieval)
- Spatial resolution limited by pixel size

\textbf{Cloetens et al. (1999):} \ ESRF, ID19, 18 keV
Polystyrene foam 0.7x0.5x1mm\(^3\)
1.4T wiggler, \( B \sim 7 \times 10^{14} \) ph/s/m\(r^2/\)mm\(^2/0.1\% @100mA\)
4x700 images at 25 sec/image

\begin{itemize}
\item [\hspace{1.5cm}] \textbf{Shen 8/30/2002}
\end{itemize}
Phase Contrast Microscopy by Defocusing

*Allman et al. JOSA (2000).* APS, 2-ID-B, 1.8 keV

spider silk fiber: $\phi 1.7 \mu m$

retrieved phase: 2.5 rad
Diffraction Microscopy

- Diffraction microscopy is analogous to crystallography, but for noncrystalline materials

- Coherent diffraction from noncrystalline specimen: => continuous Fourier transform

- Spatial resolution: essentially no limit. (only limited by \( \Delta \lambda / \lambda \) and weak signals at large angles)

- Coherence requirement: coherent illumination of sample

- Key development: oversampling phasing method coherent flux!!

Miao et al. (1999) >>> soft x-rays, reconstruction to 75 nm
Diffraction Microscopy

most recent results

Miao et al. (2002)

reconstructed image: to d~7nm resolution

Gold: 2.5\,\mu m \times 2\,\mu m \times 0.1\,\mu m

\[ \lambda = 2 \, \text{\AA} \]

SPring-8 undulator BL29XU: standard 140 periods \[ \lambda_u = 3.2 \, \text{cm} \]
\[ B=2 \times 10^{19} \, \text{ph/s/mr}^2/\text{mm}^2/0.1\% \, @100\text{mA} \]
For Au, exposure time 50 min, d~7nm
But: for C, \( (Z_c/Z_{\text{Au}})^2 \sim 1/173 \Rightarrow 6 \text{ days}!! \)
Coherent diffraction microscopy: Miao et al. (2002).

Two nickel plates: 2.8x2.6x1.2µm³
SPring-8, BL29XU

Reconstructed to 55nm resolution in 3D, based on 30 frames in 5° steps, 20 min/frame, ~10hrs.

⇒ Single molecule imaging ??
More Phase Contrast … …

- **Fourier Transform Holography**
  Leitenberger & Snigirev (2001)

- **Coherent nanocrystals diffraction**
  Robinson et al. (2001):
  1\(\mu\)m Au nanocrystal

- Imaging of shape and strain in nanocrystals
- particle-size broadened Bragg peaks help solving phase problem due to oversampling
Reconstruction of the Shapes of Gold Nanocrystals Using Coherent X-Ray Diffraction

I. K. Robinson, I. A. Vartanyants, G. J. Williams, M. A. Pfeifer, J. A. Pitney

Department of Physics, University of Illinois, Urbana, Illinois 61801

FIG. 2 (color). Stages of reconstruction of the diffraction data. (a) Coherent x-ray diffraction pattern surrounding the specular (111) Bragg reflection of a 1 μm gold nanocrystal, measured without a beamstop. (b) Symmetrized data. (c) Data filtered by multiplication by a circular Gaussian function. (d)–(f) Calculated diffraction patterns obtained by the inversion algorithm.

FIG. 3 (color). Reconstructed real-space projected images of the gold nanocrystals displayed on the same scale. (a), (b) SEM images of larger Au particles. (c) Size of the "support" constraint used in the inversion routines. (d)–(f) Real-space images obtained by inversion of the data in Fig. 2(c); the Fourier transforms of these images are the diffraction patterns shown in Figs. 2(d)–2(f).
Partial coherence => small areas of high intensities in reconstructed images.
Strain profiles in epitaxial films from x-ray Bragg diffraction phases

I. Vartanyants, C. Ern, W. Donner, and H. Dosch
Max-Planck-Institut für Metallforschung, Heisenbergstrasse 1, 70569 Stuttgart, Germany and Institut für Theoretische und Angewandte Physik, Pfaffenwaldring 57, 70550 Stuttgart, Germany

W. Caliebe
Hamburger Synchrotron Radiation Laboratory (HASYLAB), D-22603 Hamburg, Germany

FIG. 1. Diagram of the Gerchberg–Saxton algorithm
Model Free Strain Profile?

Shen & Kycia (1997) PRB 55, 15791.
**ERL Spatial Coherence**

- **ESRF emittance (4nm x 0.01nm)**
- **ERL emittance (0.015nm)**
- **Diffraction limited @ 8keV**

**Diffraction limited source:**
\[ 2\pi\sigma'\sigma = \frac{\lambda}{2} \quad \text{or} \quad \varepsilon = \frac{\lambda}{4\pi} \]

**Almost diffraction limited:**
\[ 2\pi\sigma'\sigma \approx \lambda \quad \text{or} \quad \varepsilon \approx \frac{\lambda}{2\pi} \]

**Cornell ERL:**
- **diffraction-limited source** \( E < 6.6 \text{ keV} \)
- **almost diffraction-limited to** \( 13 \text{ keV} \)
Spatial Coherence

– a few definitions

$2\sigma' \cdot 2\sigma ~ \lambda$

$\Delta l = \sigma' \cdot 2\sigma = \lambda/2$

=> X-ray beam is **spatially coherent**
if phase-space area $2\pi\sigma'\sigma < \lambda/2$

**Diffraction limited source:** $2\pi\sigma'\sigma = \lambda/2$ or $\varepsilon = \lambda/4\pi$

**Almost diffraction limited:** $2\pi\sigma'\sigma \sim \lambda$ or $\varepsilon \sim \lambda/2\pi$
Source Emittance and Brilliance

⇒ **Phase-space Emittance:**

*EM wave:* \( \mathbf{E}(\mathbf{r}, t) = E_0 e^{i(k \cdot \mathbf{r} - \omega t)} \)

\[ \varepsilon_x = \sigma_x \sigma_x', \quad \varepsilon_y = \sigma_y \sigma_y', \quad \varepsilon_\tau = \sigma_\tau \sigma_E / E \]

⇒ **Brilliance:** photon flux density in phase-space

\[
\text{Average} \quad B = \frac{F_n}{(2\pi)^2 \varepsilon_x \cdot \varepsilon_y} \\
\text{Peak} \quad \hat{B} = \frac{F_n}{(2\pi)^3 \varepsilon_x \cdot \varepsilon_y \cdot \varepsilon_\tau}
\]
Benefits of ERL to XRM

⇒ Brings high coherence to hard x-ray regime
⇒ Better optical performance for STXM & µ-probe
⇒ Phase imaging & microscopy
⇒ Far-field diffraction microscopy
⇒ Holographic techniques
⇒ Time-resolved and flash microscopy
⇒ Larger depth of focus for tomography & 3D structures
⇒ Coherent Crystallography, etc.
Micro-focusing

\[ \delta \theta \ll \frac{\sigma_x}{D_1} = 3.9 \, \mu m / 40 \, m = 0.1 \, \mu rad \]
High Resolution X-ray Microscopy?

TEM like microscopy for hard X-rays?

Would it be possible to image atomic planes (atoms) in a crystal thin enough for X-rays?

TEM without sample preparation !!!
Summary

- X-ray microscopy is an exciting field due to advances in focusing optics, 2D detectors, better sources, precise mechanics, & phasing algorithms

- Lots of ‘old’ ideas for TEM and optical microscope are now being tested and applied for hard x-rays

- Lots of application possibilities …

- CHESS can make substantial contributions due to our existing interests in optics, detectors, ERL, x-ray physics, phasing methods, & nanofabrication
<table>
<thead>
<tr>
<th>Microscope</th>
<th>Incident beam</th>
<th>Sample</th>
<th>Detected beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microscope</td>
<td>condensed</td>
<td>stationary</td>
<td>transmitted</td>
</tr>
<tr>
<td>Imaging</td>
<td>plane or spherical wave</td>
<td>stationary</td>
<td>transmitted, refracted</td>
</tr>
<tr>
<td>Scanning Probe</td>
<td>focused</td>
<td>scanned</td>
<td>transmitted, fluorescence, or refracted</td>
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<tr>
<td>Diffraction</td>
<td>coherent</td>
<td>stationary</td>
<td>scattered</td>
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<tr>
<td>Interferometer</td>
<td>split</td>
<td>stationary</td>
<td>interference</td>
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