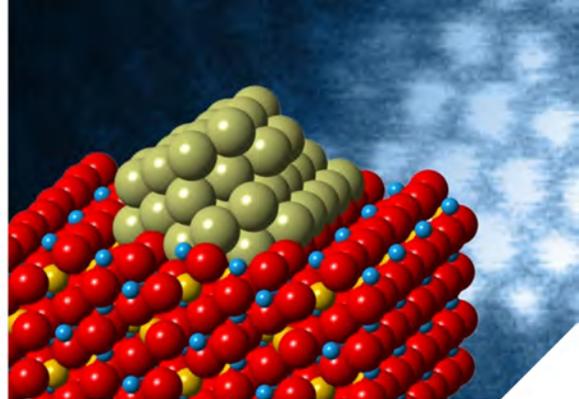
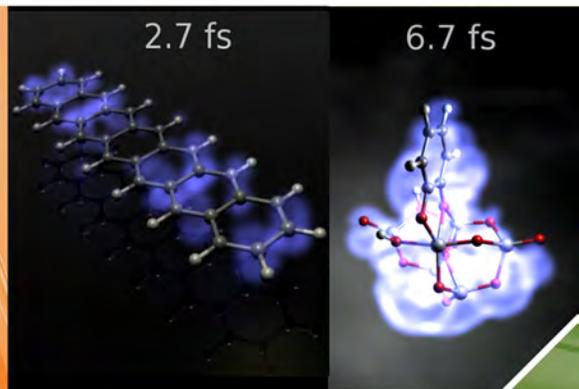


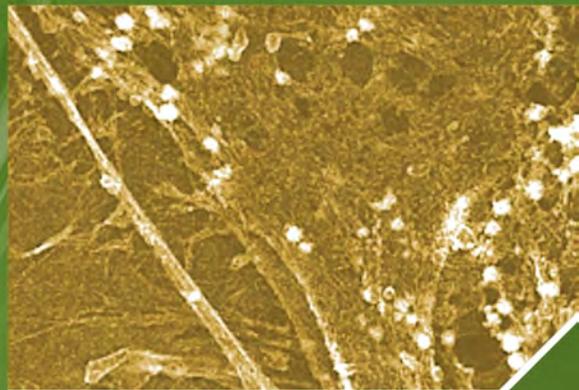
Workshop Summary Report



Dynamic Processes in Biology, Chemistry, and Materials Science: Opportunities for UltraFast Transmission Electron Microscopy



*A report from the EMSL Ultrafast Transmission
Electron Microscopy workshop, June 14-15, 2011*



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UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

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**Dynamic Processes in Biology,
Chemistry, and Materials Science:
Opportunities for UltraFast
Transmission Electron Microscopy**
Workshop Summary Report

June 14-15, 2011

Prepared for the U.S. Department of Energy's Office of Biological and
Environmental Research under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

This report summarizes a 2011 workshop held at the Environmental Molecular Sciences Laboratory (EMSL) in Richland, Washington, that addressed the potential role of rapid, time-resolved electron microscopy measurements in accelerating the solution of important scientific and technical problems. A series of U.S. Department of Energy (DOE) and National Academy of Science workshops have highlighted the critical role advanced research tools play in addressing scientific challenges relevant to biology, sustainable energy, and technologies that will fuel economic development without degrading our environment. Among the specific capability needs for advancing science and technology are tools that extract more detailed information in realistic environments (*in situ* or *operando*) at extreme conditions (pressure and temperature) and as a function of time (dynamic and time-dependent). One of the DOE workshops, “Future Science Needs and Opportunities for Electron Scattering: Next Generation Instrumentation and Beyond,” specifically addressed the importance of electron-based characterization methods for a wide range of energy-relevant Grand Scientific Challenges. Boosted by the electron optical advancement in the last decade, a diversity of *in situ* capabilities already is available in many laboratories. These capabilities enable the investigations of biological and chemical processes *in situ* with the high spatial and spectroscopic resolution provided by transmission electron microscopy (TEM). The remaining major capability gap is the lack of time resolution. State-of-the-art *in situ* TEM instrumentation allows time resolution of seconds or milliseconds at best. Present capabilities are far removed from the natural time scale on which processes on a microscopic level occur which is between microseconds (μs) to attoseconds (as).

In an effort to address current capability gaps, EMSL, with support from FCSD, the Fundamental & Computational Sciences Directorate at PNNL, organized an “Ultrafast Electron Microscopy Workshop,” held June 14-15, 2011, with the primary goal to identify the scientific needs that could be met by creating a facility capable of a strongly improved time resolution with integrated *in situ* capabilities. The workshop brought together more than 40 leading scientists involved in applying and/or advancing electron microscopy to address important scientific problems of relevance to DOE’s research mission. This workshop built on previous workshops¹ and included three breakout sessions identifying scientific challenges in biology, biogeochemistry, catalysis, and materials science—frontier areas of fundamental science that underpin energy and environmental science—that would significantly benefit from ultrafast transmission electron microscopy. In addition, the current status of time-resolved electron microscopy was examined, and the technologies that will enable future advances in spatio-temporal resolution were identified in a fourth breakout session.

The major conclusion of the workshop was that significant scientific progress can be expected in each of the four scientific areas mentioned above by the development of an ultrafast transmission electron microscope capability (UTEM) for time-resolved, *in situ* measurements capable of picosecond-scale image acquisition. Such advances are critical for understanding fundamental processes in biology, biogeochemistry, chemistry, and materials science. For example, charge transfer and intermediate states, which can be characterized by the UTEM, are critical for understanding catalytic processes in biology and chemistry that could result in higher efficiency for industrial processing. High-impact applications of the UTEM will provide important insights regarding the efficient energy transduction mechanisms, including the assembly and molecular actions of supramolecular protein machines in biology. A better understanding of the mechanism of action of cellulases has the potential to develop more efficient enzymes for the enzymatic deconstruction of plant cell walls into their fermentable sugar building blocks. The UTEM will provide the spatial and temporal resolution needed to move a generation of hypotheses from *in silico* to *in situ*. Combining enzyme simulation with observation provides the data foundation upon which engineering strategies to accelerate economic production of biofuels can be based. UTEM will also provide insight into interfacial electron transfer to mineral surfaces in

¹ <http://science.energy.gov/bes/news-and-resources/reports/workshop-reports/> and <http://science.energy.gov/bes/news-and-resources/reports/basic-research-needs/>.

biogeochemistry and dynamic and time varying processes in catalysis. Phonon mediated processes, also accessible for UTEM, are essential for understanding mechanical behavior as well as radiation effects in both engineering and biological materials. These processes happen on an atomic or on a nanometer scale but are embedded in larger scale processes, such as interaction between cells in microbial communities. These larger scale processes, which occur on a micrometer length scale and a microsecond timescale, are also observable with UTEM. In addition to the obvious advantages of high-resolution time-resolved data collection, ultra-fast measurements will enable new types of *in situ* microscopy including the ability to make measurements in extreme environments and live cells. The inherent minimization of damage during time-resolved measurements is particularly important for studies of biological systems and for *in situ* real time measurements of chemical processes, such as catalytic reactions.

The ultrafast TEM capabilities that were discussed in the workshop build on established technologies, such as pulsed electron emitters and aberration correction. Integrating these components with present *in situ* TEM methods will provide a significant enhancement - possessing all the same flexibility in environmental control but with many orders of magnitude improvement in combined spatio-temporal resolution. UTEM will integrate single shot and stroboscopic modes in one instrument enabling measurements on reversible and irreversible processes over a wide range of time scales, from milliseconds to femtoseconds. All the components for UTEM, such as electron optics, pulsed electron emitter and *in situ* instrumentation, are now available and the time is right for DOE to consider building an integrated UTEM facility to meet new scientific challenges.

The ability of an electron microscope to provide a direct image of a structure, or direct movie of a transient event, also provides access to new areas of scientific research that cannot be reached by other ultrafast methods, such as x-ray diffraction using the latest generation light sources, where the inversion from a diffraction pattern and the smaller scattering cross-section of x-rays compared to electrons limits the types of samples that can be studied. A further benefit of the integration of spatial and temporal lenses into an optimized UTEM is that the microscope will have capabilities for imaging, diffraction, and spectroscopy that are comparable to, and in some cases exceed, the best conventional instruments that currently exist.

DOE user facilities are well equipped for complex instrumentation such as UTEM and they have a successful record in development and operation of these instruments for the benefit of science groups in the US and abroad. EMSL is highly suited for UTEM because EMSL's experimental capabilities and scientific scope encompasses biology, biogeochemistry, chemistry, and material science, with an emphasis on integration of such capabilities to address significant, pressing problems that are facing DOE and the nation. Also EMSL's extensive experience in managing complex projects and successfully integrating these capabilities in impactful scientific outcomes makes EMSL an ideal facility to design, build and commission a UTEM capability.

This Workshop Summary provides a brief overview that documents the current state of TEM imaging capabilities and discusses the spatio-temporal and energy resolution needed for grand challenge research in biology, biogeochemistry, catalysis, and materials science. A plan for implementing a paradigm-changing UTEM capability also is proposed. A detailed technical Workshop Report will also be made available (<http://www.emsl.pnnl.gov/root/publications/workshops/>) and will feature extensive summaries describing additional science opportunities and challenges surrounding UTEM as identified by workshop participants.

Acknowledgment

The workshop was organized by:

- Bernd Kabius, EMSL, Pacific Northwest National Laboratory
- Nigel Browning, FCSD, Pacific Northwest National Laboratory
- Theva Thevuthasan, EMSL, Pacific Northwest National Laboratory
- Eric Stach, CFN, Brookhaven National Laboratory

The workshop was supported by Lou Terminello, FCSD, Pacific Northwest National Laboratory

The workshop was structured around the following scientific areas: biology and biogeochemistry (Leadership: Mike Hochella), catalysis (Leadership: Bruce Gates), and Materials Science (Leadership: George Crabtree). Common sessions covered keynote talks on these topics, as well as shorter discussions on the state-of-the-art instrumentation for UTEM. Scientific challenges were discussed in breakout session on these four topics.

Biology and biogeochemistry

James Evans, Don Baer, Jill Banfield, Haluk Beyenal, Daniel Bond, Edgar Buck, Luis Comolli, Nancy Hess, Mike Hochella, Scott Lea, Matt Marshall, James McKinley, Karin Rodland, Tanvir Shaikh, David Shuh, Tom Squier, Ray Teller, and Ping Yang.

Catalysis

Bruce Gates, Chongmin Wang, Amity Andersen, Ayman Karim, David King, Jingyue Liu, Karl Mueller, Charles Peden, Warren Pickett, Robert Rioux, Renu Sharma, Stefan Vajda, Yong Wang, Niri Govind, Robert Colby, and Ken Lopata.

Materials science

SK Sundaram, Charles H Henager, Richard J Kurtz, Scott Chambers, Matthew Olszta, Charudatta Phatak, Orlando Auciello, Christian Mailhot, Warren Pickett, Ulrich Welp, Niri Govind, Vincent Meunier, Libor Kovarik, Charles Henager, Steve Bruemmer, Danny Edwards, Shannon Goodwin, Brad Johnson, Toya Miller, Ulrich Welp, William Shelton, and George W Crabtree.

Acronyms and Abbreviations

Å	Angstrom
μs	microsecond
AIMD	<i>ab initio</i> molecular dynamics
BCC	body centered cubic
BER	Biological and Environmental Research
BES	Basic Energy Science
C _c	chromatic aberration
CCD	charge-coupled device
CMOS	complementary metal–oxide–semiconductor
C _s	spherical aberration
CZT	CdZnTe
DFT	density functional theory
DOE	U.S. Department of Energy
dpa	displacements per atom
DTEM	dynamic transmission electron microscopy
EDXS	energy dispersive x-ray spectroscopy
EELS	energy electron-loss spectroscopy
EFTEM	energy filtered transmission electron microscopy
ELNES	electron loss near edge structure
EMSL	Environmental Molecular Sciences Laboratory
eV	electron volt
EXELFS	extended energy loss fine structure
FCSD	Fundamental & Computational Sciences
fs	femtosecond
GISAXS	grazing-incidence small-angle scattering
HRTEM	high-resolution transmission electron microscopy
K	Kelvin
LLNL	Lawrence Livermore National Laboratory
MEMS	micro electromechanical systems
meV	milli electron Volt
ms	millisecond
NFS	nanostructured ferritic steels
nm	nanometer
ns	nanosecond
NSR	NO _x storage/reduction
PKA	primary knock-on atom

PNNL	Pacific Northwest National Laboratory
ps	picosecond
STEM	scanning transmission electron microscopy
STR	spatial and temporal resolution
TD-DFT	time-dependent density functional theory
TEAM	Transmission Electron Aberration corrected Microscope
TEM	transmission electron microscopy
UEM	Ultra-fast Electron Microscopy
UTEM	Ultra-fast Transmission Electron Microscope
XAFS	x-ray absorption fine structure
XANES	x-ray absorption near edge structure

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1.0 Scientific Challenges of Ultra-Fast Processes for Energy Science

The 20th century saw dramatic progress in observing and understanding the behavior of organic and inorganic matter in terms of their constituent atoms and electrons. Spurred by remarkable advances in experimental resolution of space, time, and energy and the intellectual leaps and descriptive power of quantum mechanics, atoms and electrons emerged from abstract organizational concepts at the beginning of the last century to practical building blocks that can be observed, assembled, and manipulated in a multitude of ways. However, most of humankind's knowledge of atoms and electrons is in the equilibrium or near-equilibrium limit, where behavior changes slowly with time. Although it is known that chemical reactions are inherently dynamic and have been examined using optical methods for decades, probing and understanding the dynamics of biological, chemical, and solid-state processes that account for most of their functionality is in its early stages. Bond breaking and making; the transfer of energy among electronic, lattice, and magnetic degrees of freedom; and the fluctuations that promote phase transformations happen on ultrafast time scales—picosecond or shorter—and far from equilibrium. They remain largely beyond our experimental and theoretical reach, particularly for methods that have the highest spatial resolution.

The crucial importance for high time and spatial resolution under *in situ* condition is indicated by frequent calls for additional dynamic and time resolved measurements in U.S. Department of Energy (DOE) and related National Academy workshop reports. These calls and reports cover a wide range of topics from instrumentation¹ to addressing BER specific scientific topics relevant to biology^{2,3}, biogeochemistry⁴, catalysis, carbon capture, and general DOE related topics such as compact light sources, electron scattering, solid state lighting and energy storage⁵. Although geological and biological processes have time scales of days, months, and years, the molecular- and atomic-scale mechanisms, such as protein folding and electron transfer processes that influence these longer scale behaviors, occur much more quickly. Therefore, the dynamics of processes that impact subsurface contaminant transport^{2,6}, carbon capture and storage, as well as other aspects of biology, cover a large time scale and will benefit from rapid time resolved and *in situ*¹ measurements. The National Academy of Sciences report¹ on advanced instrumentation and facilities frequently noted the importance of dynamical measurements and specifically called out the need for dynamic electron microscopy. Not only will time-resolved measurements advance the ability to measure important processes, they will both stimulate new theoretical work and provide the basis for testing and verifying these theoretical efforts. Observing dynamic behavior across space and time scales is an essential first step in explaining and ultimately controlling far-from-equilibrium phenomena and functionality.

The natural time scale of dynamic processes depends on the area of interest, from attoseconds to femtoseconds for electronic transitions; femtoseconds to picoseconds for atomic, molecular, and lattice dynamics; picoseconds to nanoseconds for magnetic and ferroelectric polarization reversal; and from nanoseconds to microseconds for atomic diffusion processes involved in nucleation and growth phenomena. The natural length scale for dynamic processes ranges from the atomic and molecular scale, 0.1-10 nm, up to the scale of interactions between biological cells and grains in metallic alloys.

The dynamic responses of materials typically strongly interact with each other—electronic, structural, and spin degrees of freedom cooperate in chemical reactions, phase transitions, and polarization reversals. This interaction dramatically affects the time scale of a given phenomenon. For example, in bond-breaking chemical reactions, photoexcitation of a diatomic molecule to an excited electronic state may require only attoseconds, but the subsequent separation of the molecule as it relaxes toward dissociation requires several vibrational cycles on the picosecond time scale. For more complex chemical reactions requiring bond breaking and bond forming, the time scale can be longer to accommodate the more complex atomic rearrangement. The strong interaction between electronic, structural, and magnetic degrees of freedom effectively slows down fast electronic processes and provides additional experimental signatures of the

composite dynamics. Full characterization of the time sequence and interaction of the dynamic responses requires integrating information from separate probes of each degree of freedom. Figure 1 offers an overview of the time and length scales of dynamic process in the major scientific topics—biology and biogeochemistry, catalysis, and materials science—on which this workshop was focused and where a project can access each scientific challenge.

Opportunities for capability expansion through UTEM in the time/space domain: dynamic processes in Biology, Chemistry and Materials Science

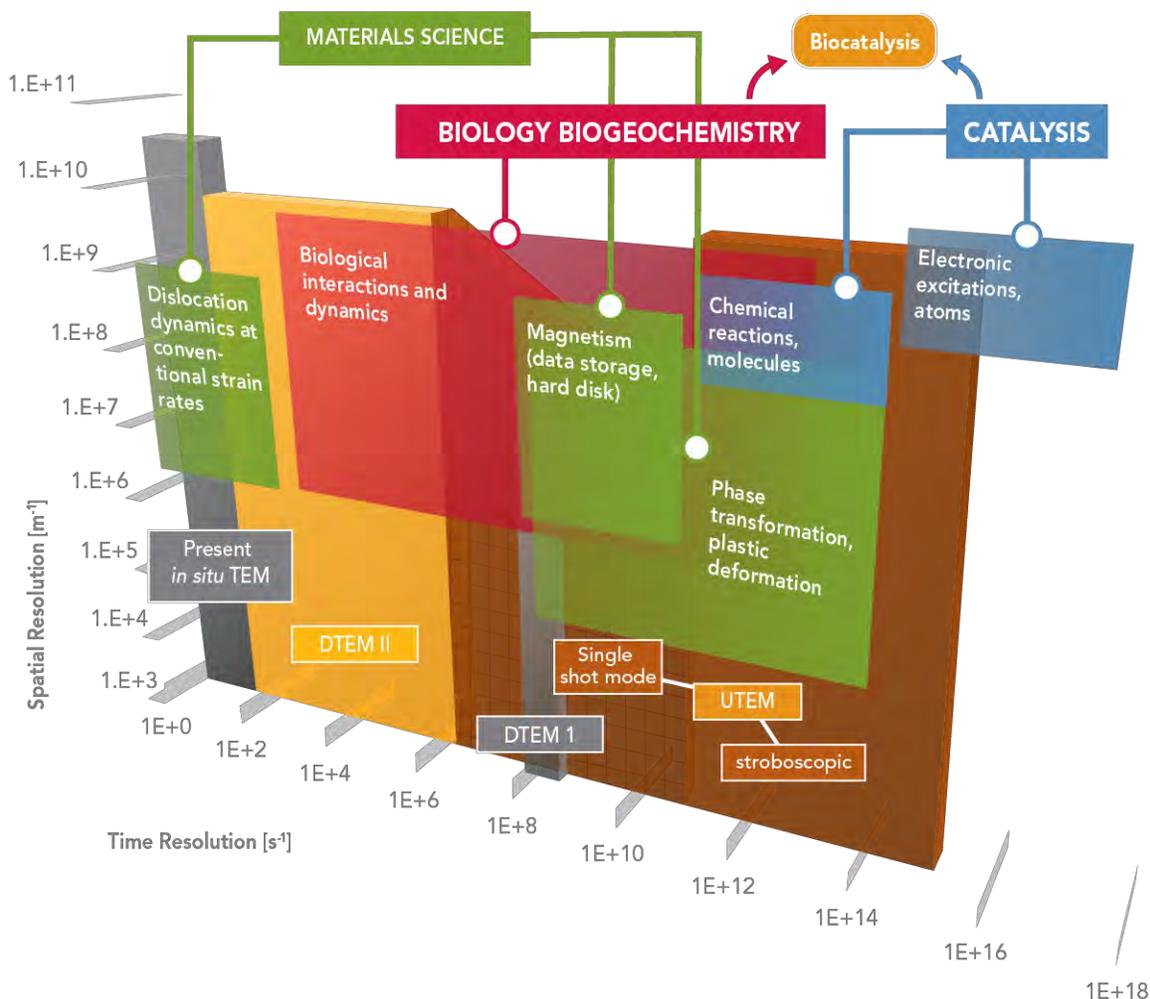


Figure 1. Scientific challenges, dynamic process, and their intrinsic time and length scales. The cuboids in the background (present *in situ* TEM, DTEM I, DTEM II, and UTEM) indicate which technology must be used to access certain processes. DTEM I is the dynamic transmission electron microscope (DTEM I) at Lawrence Livermore National Laboratory (LLNL). DTEM II development was started at the University of California, Davis (UC-Davis) and is currently being transferred to PNNL. The proposed, new UTEM capability will build on prior projects and will enable observation of shorter time scale processes that are beyond the reach of current capability.

While the need for dynamic information applies to most areas of science, the workshop reported here focused on electron microscopy and the science need in three specific areas. In each area, several topics were identified for which ultrafast transmission electron microscopy could enhance scientific discovery:

Biological Sciences and Biogeochemistry

Cellular responses to changes in their environment, such as microbial communities or multicellular eukaryotic organisms, are one of the great challenges in biological sciences. These responses include complex dynamic processes involving synthesis, assembly, and turnover of the cellular machinery. An integrated approach including proteomics, structural biology, and UTEM will advance our understanding of cellular response to changing environmental signals. Critical to these goals are the high time and spatial resolution of the UTEM concept. Such measurements offer an ability to validate biological function and facilitate the interoperability of biological modules and processes in both lab based and environmental systems.

UTEM is expected to permit measurement of high-resolution structures of individual proteins, macromolecular complexes, organoids, and viruses in solution without the need for crystallization. These new methods may permit “diffract and destroy” imaging where the diffraction pattern is collected for individual molecules prior to the onset of radiation induced damage or motion. Pulsed beam operation also minimizes the electron dose because the sample is only exposed to the electron beam for data acquisition. Ultimately, it is anticipated that these new methods will enable the creation of movies of protein conformational changes related to catalysis, as well as the identification of macromolecular structures in viruses or intact living microbes. UTEM allows access to the time and length scale of molecular machines permitting measurements of assembly and functional dynamics.

Several important roles have been identified for UTEM including: nanoparticle nucleation and transport, imaging of living tissue, determining the structure of individual proteins and protein dynamics, measurements of functional dynamics of molecular machines, and examination of diversity in microbial communities.

Geochemical and biogeochemical processes play major roles in the Earth’s chemical cycles and important processes including contaminant transport, bioremediation, biocatalysis, CO₂ sequestration and bioenergy production. Understanding these systems requires the unique spatial/time resolution of UTEM for the aforementioned biological processes while interacting with a geological environment (pressure, temperature, inorganic compounds).

Catalysis

Catalysts are critical components of many current technologies and essential components of sustainable energy systems ranging from fuel cells and batteries to turning biomass into useful chemicals or fuels. Catalysis involves many dynamic and time-varying processes, of which many can be examined by UTEM approaches. Relevant times for catalytically important processes range from femtoseconds to hundreds of seconds. It is particularly relevant to understand and visualize transient processes, such as structural changes during catalysis operation, substrate catalyst interactions, and intermediate states. In addition, the application of UTEM methods can serve to minimize any perturbing impacts of the electron beam *in situ* studies. The types of detailed information that can be available from UTEM should facilitate advancing theoretical understanding and design of next-generation catalysts by allowing theory, characterization and function to be integrated. The development of UTEM will both require and enable a new type of pump-probe experiment, not generally applied to catalysis work, to be developed and exploited.

Materials Science

Materials science has been a traditional domain of electron microscopy. Historically, the structures of a material and material interfaces have been considered in a mostly static manner, with small fluctuations around that static structure being considered. Increasingly, it has been recognized that dynamic processes determine many materials and interfacial properties, ranging from material cracking to photoexcitation processes. Dynamic processes identified as important for UTEM study by workshop participants included the solid-liquid interface, crack propagation, resistive switching in memory materials, phase transitions, fluctuations in correlated electron materials, radiation damage, and structures (including defects) of nanomaterials.

Microscopy Opportunities and Challenges

As the world embraces and makes more routine use of the exceptionally high spatial resolution afforded by the new breed of aberration-corrected electron microscopes, there remain two exciting frontiers in electron imaging: 1) *in situ* measurements and 2) imaging in very short time domains. The former capability (*in situ* measurements) is a simple extension of current electron microscopy technology and currently is being developed by a number of commercial partners (such as Hummingbird Scientific, FEI, and JEOL). Conversely, the latter capability (short time frame microscopy) is equally exciting but will require new electron sources to reach the picosecond timescales that allow new insights into irreversible materials and biological phenomena of interest to DOE.

Scientific Impact of Electron Microscopy and the Challenge of Ultrafast Measurements

Electron microscopy provides probes of electronic, structural, and polarization degrees of freedom at high spatial resolution. Spherical and chromatic aberration correction allows unmatched focusing to angstrom (\AA) and sub- \AA spatial resolution for imaging the structure and motion of isolated nonperiodic objects, such as atoms, molecules, defects, interfaces, and amorphous structures. Electron diffraction allows detailed structural characterization of periodic systems using much lower intensity electron beams. Electron energy loss spectroscopy (EELS) probes the electronic excited states of materials with atomic resolution, and Lorentz imaging and holography probe magnetic states with nm resolution. Collectively, these electron probes cover most phenomena in materials dynamics. Often, these probes can be applied to the same sample in the same experimental apparatus, avoiding complications due to sample variation. Electron interaction with matter is much stronger than that of x-rays, making an electron beam probe much more efficient for analyzing small volumes.

The challenge in applying electron microscopic imaging to dynamic molecular and atomic processes is achieving electron pulses of sufficiently high intensity and short duration to freeze the electronic, structural, or chemical motion. Remarkable progress in producing short pulses by laser-induced photoemission has allowed the time resolution of electron imaging to be pushed through the microsecond to the nanosecond regimes.⁷⁻⁹ Progress in ultrafast lasers and photocathode materials now brings the prospect of UTEM at picosecond time scales well within reach, opening new time regimes for probing ultrafast dynamic behavior. Stroboscopic illumination already has achieved femtosecond resolution¹⁰, a major advance for systems that are perfectly reversible for millions of repetitions. One of the Grand Challenges in ultrafast electron microscopy is achieving comparable time resolutions for processes that are not perfectly reversible. In this report, we explore the new scientific horizons that ultrafast electron microscopy opens for capturing the dynamics of materials at picosecond and faster times scales in three broad areas: biogeochemistry, catalysis, and material science.

2.0 Present Capabilities of TEM, DTEM and UTEM Concepts

During the last two decades, electron microscopy has witnessed an unprecedented number of innovations that enhanced existing approaches and introduced qualitatively new techniques. One of the most important novel technologies is aberration correction. Correction of spherical aberration C_s has been demonstrated by Haider et al.¹¹ In the years that followed, this hexapole corrector was applied to various materials science problems¹²⁻¹⁴ and is now a standard for high-resolution TEM (HRTEM). A quadrupole/octopole corrector was developed and applied by Dellby et al.,¹⁵ for scanning transmission electron microscopy (STEM) mode. Since then, aberration correction has been used to help solve diverse material science problems.¹⁶⁻¹⁸ Recently, correction of chromatic aberration has been demonstrated¹⁹ and successfully applied to improve resolution in energy-filtered TEM (EFTEM) by a factor of five. Furthermore, there has been significant progress in EELS, resulting in improved energy resolution (monochromator) and a larger field of view for electron-spectroscopic imaging²⁰ and energy-filtered imaging.²¹ Micro electromechanical systems (MEMS) technology have also been employed to fit experimental equipment into the TEM.²²

All of these new developments have benefitted *in situ* TEM by allowing more space for experimental equipment around the sample, achieving better resolution in gaseous or liquid environments²³ and thereby stimulating a significant increase in the number of publications in this field. A further indication for this trend is the diverse variety of *in situ* sample holders, which now are available and/or under development.

Many of the requirements for the investigation of dynamic processes by *in situ* TEM already are in place: spatial resolution, environment, and analytical electron microscopy and *in situ* instrumentation for TEM. While research has made these static requirements for ultrafast TEM readily available, the fundamental temporal resolution remains severely lacking. Resolving picosecond or faster dynamic process on a nanometer or an atomic scale requires short intense electron pulses—a frontier now poised for rapid progress. Dynamic processes on a nanometer or an atomic scale are occurring on a time scale between nanoseconds and attoseconds, while most *in situ* experiments to date offer a time resolution up to 30 frames per second with a spatial resolution of about 0.2 nm²⁴. In characterizing a TEM for observing dynamic processes, it is useful to define the product of spatial and temporal resolution (STR) for this instrument: $3 \cdot 10^{-2} \text{ s} \cdot 10^{-10} \text{ m} = 3 \cdot 10^{-2} \text{ m} \cdot \text{s}$.

Examples demonstrating the need for UTEM

The enzymatic deconstruction of plant cell walls into their fermentable sugar building blocks is highly relevant to BER's bioenergy mission. Enzyme costs are a key cost bottleneck for production of lignocellulosic biofuels. To design more efficient enzymes, we need to better understand the mechanism of action of cellulases. Currently, computational simulations have been performed that lead to hypotheses about how these important enzymes interact with and catalyze deconstruction of their substrates (see Figure 2²⁵). The UTEM will provide the spatial and temporal resolution needed to move a generation of hypotheses from *in silico* to *in situ*. Combining enzyme simulation with observation provides the data foundation upon which engineering strategies to accelerate economic production of biofuels can be based.

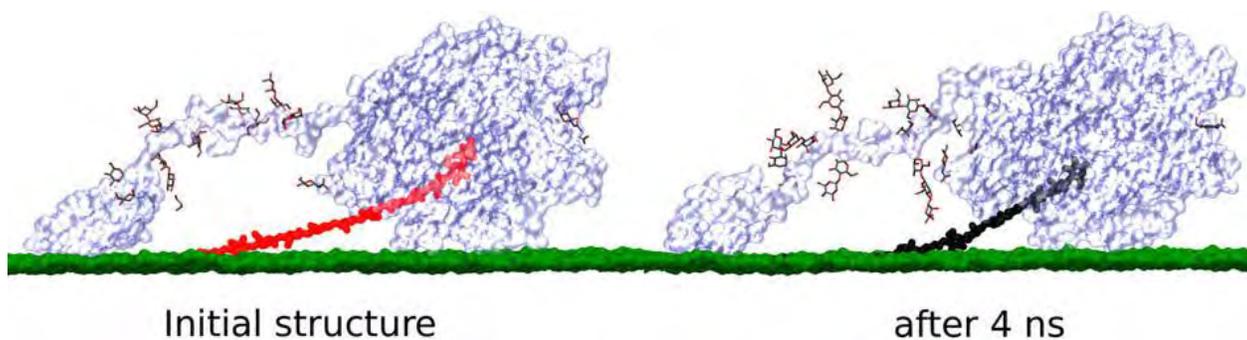


Figure 2. The initial conformation (left) of the substrate chain (shown in red); (at right) the final conformation (shown in black).²⁵ This is a modeled depiction, but the UTEM approach would provide actual, dynamic conformational detail of this process at the nanosecond timescale.

A material science example demonstrating the limitation of the present approach can be seen in Figure 3, which shows two consecutive frames taken from a movie of grain boundary movement in Au.²⁶ The grain boundary moves during the time between these frames ($\sim 3 \times 10^{-2}$ s) by approximately two nanometers. This process involves thousands of atoms moving and reconnecting to the lattice of the adjacent grain. Present instrumentation shows only the rapid movement of the grain boundary, but delivers no insight into the mechanism of grain boundary movement and intermediate steps.

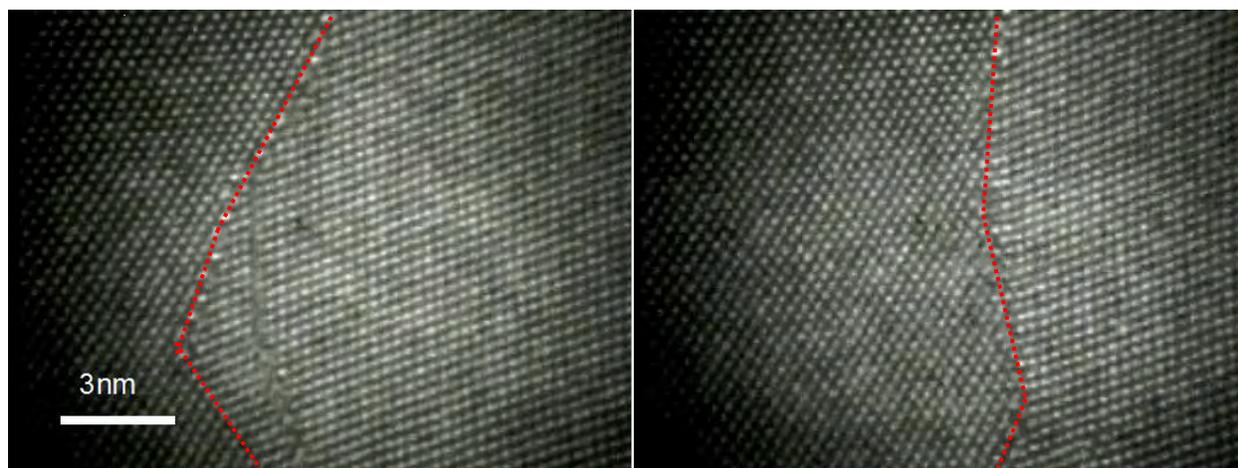


Figure 3. Grain boundary movement in Au: These high-resolution TEM images show that a grain boundary (marked by the dotted red line) moves several nanometers between two frames of the movie recorded under *in situ* conditions.²⁶ The details of the mechanism of grain boundary movement are beyond the time resolution of this experiment, but could be observed using the proposed UTEM approach.

This time resolution can be improved to a certain extent by charge-coupled device (CCD) cameras with faster frame rates. A direct complementary metal-oxide semiconductor (CMOS) camera, developed for the transmission electron aberration-corrected microscope (TEAM) project, demonstrated atomic resolution with a frame rate of 400 Hz.²⁷ This approach is finally limited by the electron emission rate of the electron source. If we assume a current of 100 nA for a standard Schottky field emitter, an image size of 512^2 , and ~ 100 electrons per pixel to obtain a reasonable image quality, a time resolution of 100 μ s can be achieved. By accepting noisier images or increasing the electron beam current, this limit may be extended by one or two orders of magnitude. However, this approach is not suited for achieving the time resolution required for the scientific challenges summarized in this report.

Further improvement in time resolution requires an electron source that can deliver an electron beam current orders of magnitude higher than the current that can be extracted from present field emission cathodes. Photoemission has demonstrated that it can meet this requirement²⁸.

There are two approaches that enable a time resolution in the range of nanoseconds to femtoseconds:

- Stroboscopic: Each pulse contains only one (or a few) electron(s). This method which has been termed “4D electron microscopy,” has demonstrated femtosecond resolution¹⁰ but can only be applied to processes that are completely reversible. Although the STR in this case is $10^{-15} \text{ s} * 10^{-10} \text{ m} = 10^{-25} \text{ m*s}$ it requires $\sim 10^8$ cycles to obtain an image.
- Single shot: Each pulse contains a large number of electrons sufficient for a wide field of view image. Bostanjoglo and co-workers invented this approach and Lawrence Livermore National laboratory (LLNL) and UC-Davis have used it in recent years to develop a dynamic transmission electron microscope (DTEM) for both reversible and irreversible processes.²⁸ The recent DTEM project at LLNL made a major advance in achieving a combined STR of $10^{-8} \text{ s} * 10^{-8} \text{ m} = 10^{-16} \text{ m*s}$.^{29,30} A second DTEM project at UC-Davis (the microscope will soon be relocated to EMSL) aims for an STR of 10^{-16} m*s although in this case the temporal and spatial resolution aimed at a different set of parameters ($10^{-6} \text{ s} * 10^{-10} \text{ m}$).

As it allows a broad scope of systems to be investigated, a combined instrument that affords both the single shot and the stroboscopic approaches appears to be the best choice for a DOE facility. The availability of both modes is important because with present technology femtosecond resolution can only be achieved in stroboscopic mode, while single-shot mode allows access to irreversible processes at nanosecond resolution. The UTEM would push the limit of time resolution in single-shot mode to picoseconds. A TEM with both capabilities offers access to intermediate states of chemical reactions on an atomic scale as well as to protein folding and cell interactions on a nanometer or micrometer scale, respectively.

3.0 Comparison with x-ray Sources

The recent implementation of free-electron lasers (FELs) to generate ultrafast pulses of highly brilliant x-rays has enabled pump-probe experimentation beyond the typical samples amenable to synchrotron light sources.³¹ For instance, only one year after coming online in 2010, the Linac Coherent Light Source (LCLS) demonstrated the first coherent x-ray diffraction from individual nanocrystals³² and large isolated viruses³³. Both of these nanoscale test samples were previously undetectable on third-generation synchrotron light sources due to their size. Although the first experiments at LCLS only achieved 0.8 nm spatial resolution for protein nanocrystals, atomic resolution theoretically is possible with planned improvements to the beam that are already in progress.³³

As shown in **Figure 4** the atomic cross-sections for carbon vary as a function of wavelength (and energy) with orders of magnitude difference between x-rays and electrons. For both types of information sources, the elastic scattering provides phase contrast imaging and diffraction amplitudes used for structural analysis, while the inelastic events can be used for spectroscopy and Z-contrast imaging for electrons.

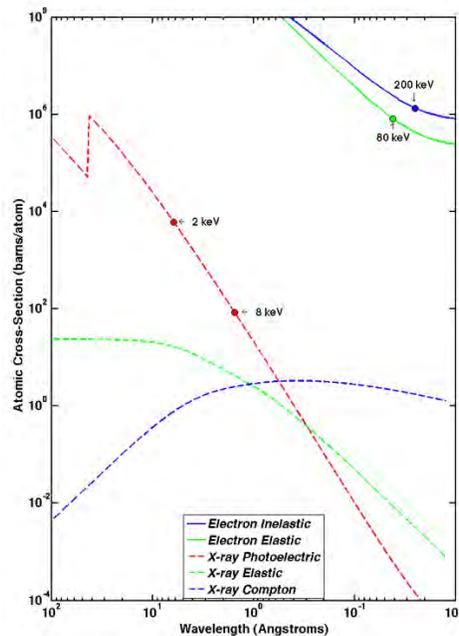


Figure 4: Comparison of atomic cross-sections (element = carbon) for electrons and x-rays as a function of wavelength. Absorption, Elastic and Inelastic scattering cross-sections are displayed (red, green, and blue, respectively).

Because the energy deposited onto a sample (and by extension radiation damage) is directly proportional to the amount of inelastic scattering events by the incident electrons or x-rays,³⁴ the more signal produced from a single elastic or inelastic scattering event the better. For x-rays, both the photoelectric and Compton cross-sections are related to inelastic scattering events. By this standard, 0.15 nm x-rays (8 keV) are 1000 times worse than 200 keV electrons (0.0025 nm). It should be noted that the wavelength of accelerated electrons generally is much smaller than the wavelength of x-rays used in synchrotron and FEL light sources. One accessory benefit to the smaller wavelength is an increase in the radius of the Ewald sphere for diffraction experiments that allows more faithful imaging of the two-dimensional distribution of reciprocal lattice points for thin samples.

Interestingly, the recent experiments with femtosecond x-ray pulses demonstrated the feasibility of a novel “diffract-then-destroy” imaging methodology that bypasses conventional damage mechanisms caused by high flux x-ray radiation such as Coulombic explosion of molecules.³⁵ A similar effect may occur for ultrafast electrons where the detrimental imaging effects caused by sample interaction with the electron beam, including knock-on damage, radiolysis, and hydrogen gas evolution, are anticipated to be outrun by nanosecond and picosecond electron pulses.³⁶ Additionally, the blurring effects currently caused by Brownian Motion and fluid flow during *in situ* liquid experiments of particles suspended in solution, will be mitigated by ultrafast pulses of better than 1 microsecond as the magnitude of movement during such a pulse will be below the 0.1–1 nm spatial resolution anticipated for the UTEM.

Combined, the shorter wavelengths, higher scattering cross-sections, tunable beam, and pulse parameters for electrons permit enhanced imaging conditions for many types of samples, spanning materials science and biology, wherein locality is important. The development of UTEM with pulse durations from the μs to ps time scale would enable further optimization of experimental conditions to match either the spatial and/or temporal resolution to the dynamic process of interest.

4.0 Path Forward

The three scientific area working groups indicated that ultrafast electron microscopy would play a major role in each area. In comparison to other methods, including rapid optical measurements and those enabled by a new generation of synchrotron radiation, UTEM occupies important and unique territory for obtaining the types of high spatial and high time resolution information needed to advance several areas of science. UTEM is particularly useful in investigating the dynamics of processes, particularly those far from equilibrium and including those in extreme environments, which are inaccessible to present capabilities. This includes identifying intermediate states that occur during complex processes before a system reaches equilibrium. Understanding these intermediate states is crucial for many energy-related topics, such as catalysis, biocatalysis, and biogeochemistry, where these states are used to circumvent high-energy thresholds. According to theoretical models, many materials science related processes, such as radiation damage, plastic deformation, and domain reversal, include intermediate states whose experimental tests are beyond present capabilities. The time scale reaches from nanoseconds to attoseconds for reaction steps happening on a molecular or atomic length scale. UTEM has the capability to access the range down to picoseconds in single-shot mode and will use a stroboscopic approach for femtosecond processes. This enables UTEM to improve our understanding of fast processes in a variety of scientific topics. This report focuses on contemporary energy-related challenges in key areas, including biology, biogeochemistry, catalysis and material science.

During the last decade, many components, such as aberration correctors, high brightness guns, environmental cells, and energy monochromators, have been developed to further advance TEM capabilities. Novel designs for sample holders also were introduced to enable experimental capabilities inside a TEM. These developments are improving the capabilities of TEM for *in situ* experiments. Therefore, the major topic for TEM during the next decade will be *in situ* experiments.³⁹ However, there is one major capability gap for *in situ* experiments: and that is time resolution. For most published *in situ* TEM imaging experiments, the time limit is video frame rate. The two exceptions are the femtosecond 4D UEM at the California Institute of Technology, which operates in stroboscopic mode, and the single-shot operation TEM at LLNL that is capable of 20-ns electron pulses. Both instruments are limited to either perfectly reversible processes or to a very narrow time scale, and they offer only a few types of *in situ* experiment capabilities.

The UTEM concept integrates the time resolution of these pump-probe instruments with state-of-the-art aberration correction technology, chemical analysis and the *in situ* capabilities mentioned above, thereby offering ground breaking time and spatial resolution for a large variety of *in situ* experiments. UTEM also offers a way to observe and understand structure and chemistry of radiation-sensitive systems, which are typical in biology and catalysis. For all systems where electron diffraction is faster than radiation damage, it is possible to avoid artifacts from the electron beam-sample interaction, such as amorphization and triggering or influencing chemical reactions by the electron beam.

Short laser pulses (or other trigger mechanisms such as electric fields) can provide extreme environments (temperature, pressure, high electric/magnetic fields) for a short time span. Only UTEM will be fast enough to image and analyze the system in this extreme environment. This capability will be important for scientific challenges in biogeochemistry and materials science.

The increasingly recognized need to understand time dependent processes, ranging from the second to faster than the femtosecond scale, requires development of new capabilities that can obtain time dependent information with high energy and spatial resolution. Although advanced x-ray methods provide important dynamical information, the physical characteristics of a UTEM system would allow it to provide information for many types of samples not available from other methods. Among its other strengths, observing dynamic behavior on its natural space and time scales via UTEM is an important step in explaining and ultimately controlling far-from-equilibrium phenomena and functionality.

A next-generation, ultrafast (herein defined as sub-nanosecond time scales) electron microscopy capability will close the capability gap identified above, significantly enhancing overall electron microscopy analytical and characterization performance in terms of short duration chemical transformations and other previously intractable applications, such as biological systems that could not otherwise be studied because of radiation damage. Current technologies or reasonable extensions of them can be combined to create this new generation instrument, allowing dynamic low damage measurements.

The critical components for ultra-fast measurements under *in situ* or in *operando* conditions include a pulsed electron source, instrumentation for *in situ* TEM experiments, state-of-the-art aberration correction, and a fast and efficient detection system. Pulsed electron sources for nanosecond single shot and femtosecond stroboscopic have been demonstrated. Further development is needed to enhance the number of electrons per pulse to enhance time resolution in single shot mode to picosecond level. The consequence of high electron density in single pulses is loss of spatial and temporal coherency, which can be compensated by spherical and chromatic aberration correction. These correction systems have been developed and tested as part of the Transmission Electron Aberration corrected Microscope (TEAM) project. The alignment concepts must be adapted to the special requirements of the UTEM's pulsed electron emitter to minimize loss of spatial resolution. Direct CMOS (complementary metal–oxide–semiconductor) detectors will improve detection efficiency, which is important for UTEM because of the limited number of electrons per pulse.

5.0 Recommendation

The UTEM workshop defined four major scientific areas addressing DOE's mission: biology, biogeochemistry, catalysis and materials science. Especially promising opportunities were identified in bioenergy, bioconversion, and fundamental microbial processes, where time resolved information will be invaluable to understand complex processes and, in a second step, to control and improve them. Present and developing technology in TEM instrumentation was deemed appropriate to close this capability gap by initiating the UTEM project, which targets the required time resolution and combines it with the *in situ* capabilities, high spatial and spectroscopic resolution already achieved in transmission electron microscopy. UTEM can be regarded as a critical component for the required transition of moving from static post-mortem studies to *in situ* investigations to understand dynamic processes. It is accordingly recommended that DOE move toward development of a UTEM capability as soon as practically possible.

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Appendix A

Appendix A: Workshop Participants

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