Extending the TEAM Control Room

Workshop on Remote Access to the Transmission Electron Aberration-corrected Microscope

- Background and overview
- Scientific needs at Nanoscience Centers
- TEAM operation - local and remote
- Broadband connection

the TEAM collaboration

U. Dahmen, P. Denes, A.M. Minor, C. Kisielowski, B. Freitag, M. Bischoff, H. van Lin, S. Lazar, G. Knippels, P. Tiemeijer, M. van der Stam, S. von Harrach, M. Stekelenburg, M. Haider, S. Uhlemann, H. Müller, P. Hartel, B. Kabius, D. Miller, I. Petrov, E. A. Olson, T. Donchev, E.A. Kenik, A. Lupini, J. Bentley, S. Pennycook, I.M. Anderson, A.K. Schmid, T. Duden, V. Radmilovic, Q. Ramasse, M. Watanabe, R. Erni, E.A. Stach

Workshop Goals and Outline

TEAM is important for nanoscience research facilities.

- Can we provide remote access for NSRC users? Establish access portals at 5 nanoscience centers.
- Limiting factors
  - Bandwidth (ESnet)
  - Security (National Labs)
  - Infrastructure (NSRCs)
- Scientific needs
  - Discuss scientific opportunities
  - Establish modes of operation
- Types of experiment
  - Follow-up to on-site visit (familiarity with instrument essential)
  - Data-taking (image sequence, TFS, kinetics, standard tomography, spectrum imaging,…)
- Logistics (proposal process, scheduling, local support,…)
- Mechanics (control interface, protocols,…)

Workshop structure

What is TEAM
Background + Overview

Scientific needs and capabilities at NSRCs and partner labs

Instrument operation, software, stages and support

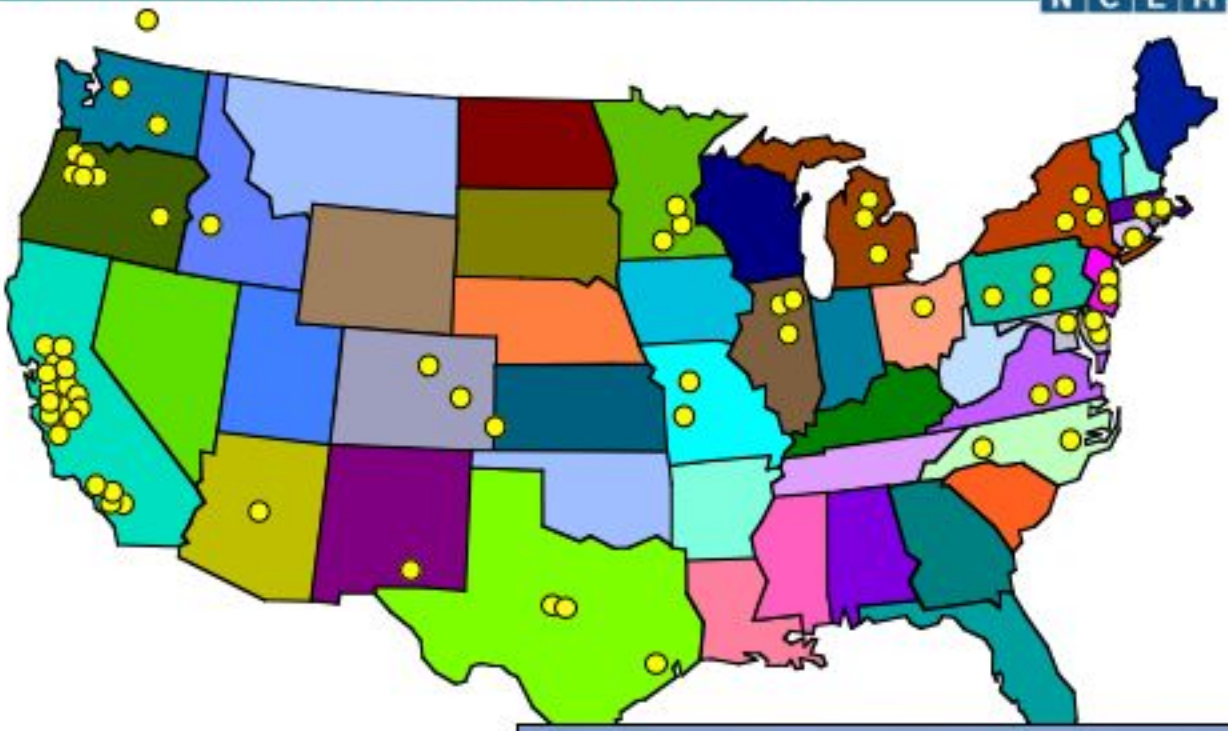
Remote operations
Networks, data transfer
Howto make it real

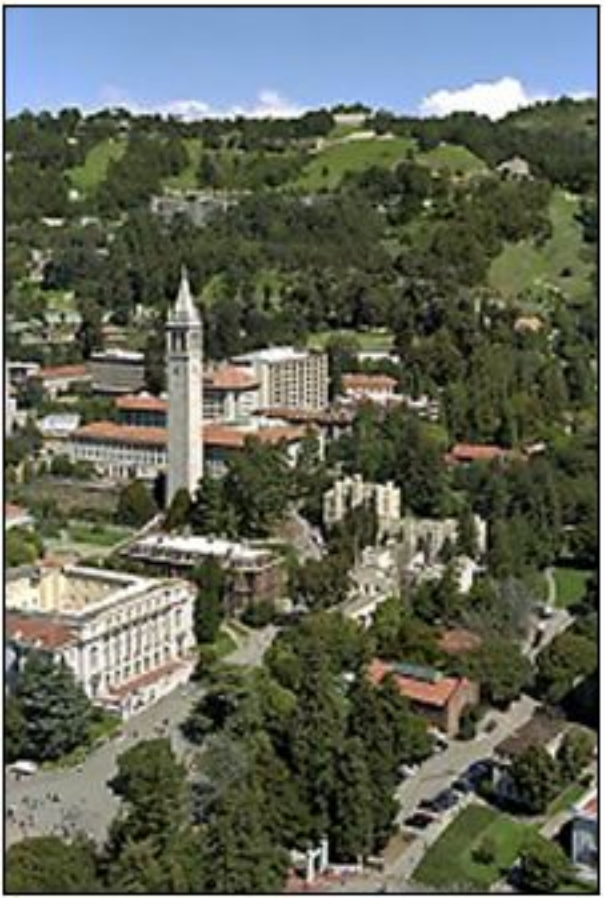
8:30 am	*Welcome, TEAM overview and workshop goals*	Uli Dahmen
8:55 am	*TEAM project status*	Peter Denes
9:20 am	*CNMS overview and needs for advanced microscopy*	Linda Horton
9:45 am	COFFEE	
10:15 am	*Foundry overview and needs for advanced microscopy*	Jim De Yoreo
10:40 am	*Electron microscopy and nano-science at ANL: new opportunities through TEAM*	Dean Miller
11:05 am	*In situ electron microscopy enabled by a TEM-SPM platform at CINT*	Jianyu Huang
11:30 am	*Overview and needs for electron microscopy at CFN*	Lihua Zhang
11:55 am	LUNCH	
1:00 pm	*The SHaRE user facility and microscopy at ORNL*	Karren More
1:25 pm	*TEAM stage: opportunities for in-situ microscopy*	Ivan Petrov
1:50 pm	*TEAM stage: prospects for remote operations*	Thomas Duden
2:15 pm	*Driving TEAM remotely: operations, alignments, feasibility*	Rolf Erni
2:40 pm	COFFEE and TEAM VISIT	
3:25 pm	*TEAM software*	Quentin Ramasse/Earl Cornell
3:45 pm	*ESNet*	Eli Dart
4:10 pm	*Practical aspects and requirements of remote microscopy operation for research oriented applications*	Masashi Watanabe
4:35 pm	*Remote microscopy at FEI*	Auke van Balen
5:00 pm	*Discussion*	Nestor Zaluzec

NCEM

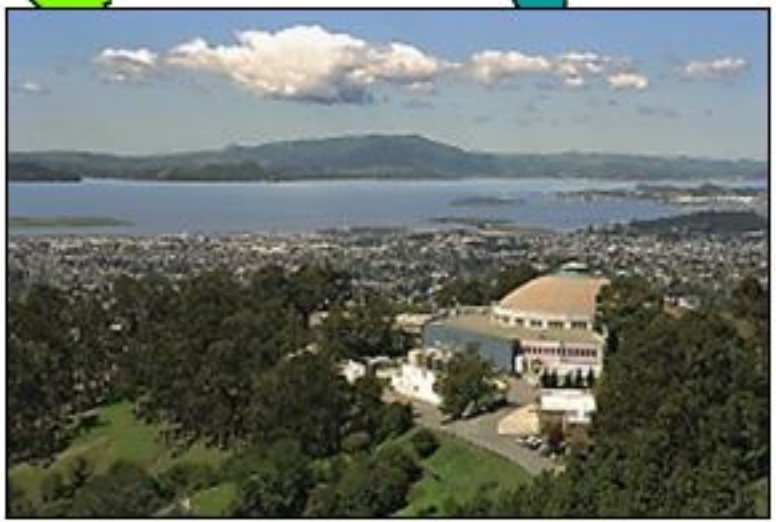
DOE user facility for electron microscopy

- Free access controlled by external Proposal Review Committee



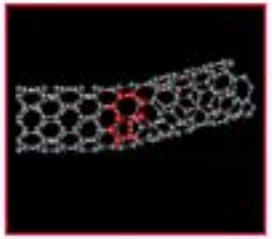


~250 users per year

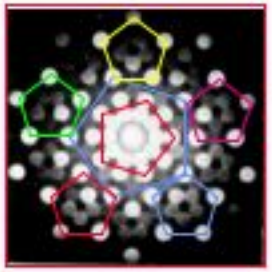


Electron Scattering

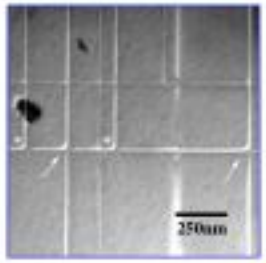
Significant achievements in materials science



- New materials
  Nanotubes



- Phase transformations
  Quasicrystals



- Defects
  Strength of crystals

Electron microscopy is an integral part of the discovery and development of new materials.

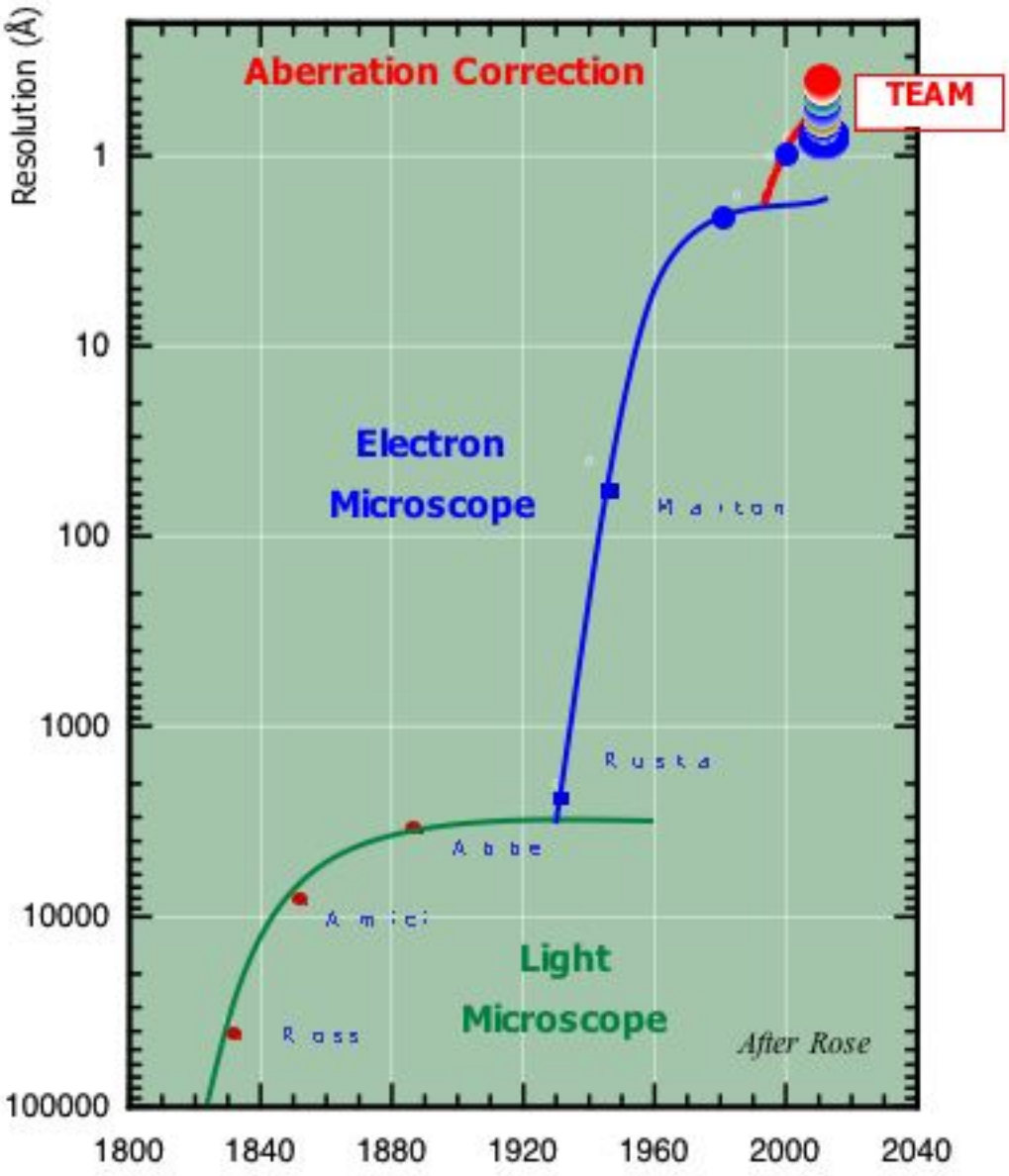
50% of all materials research utilizes TEM.

Future opportunities such as
- 3D atomic resolution,
- in-situ probing of individual nanostructures,
- ultrafast dynamics,
- hard/soft matter composites….

However, instrument performance remains limited by lens aberrations…

Historical Perspective

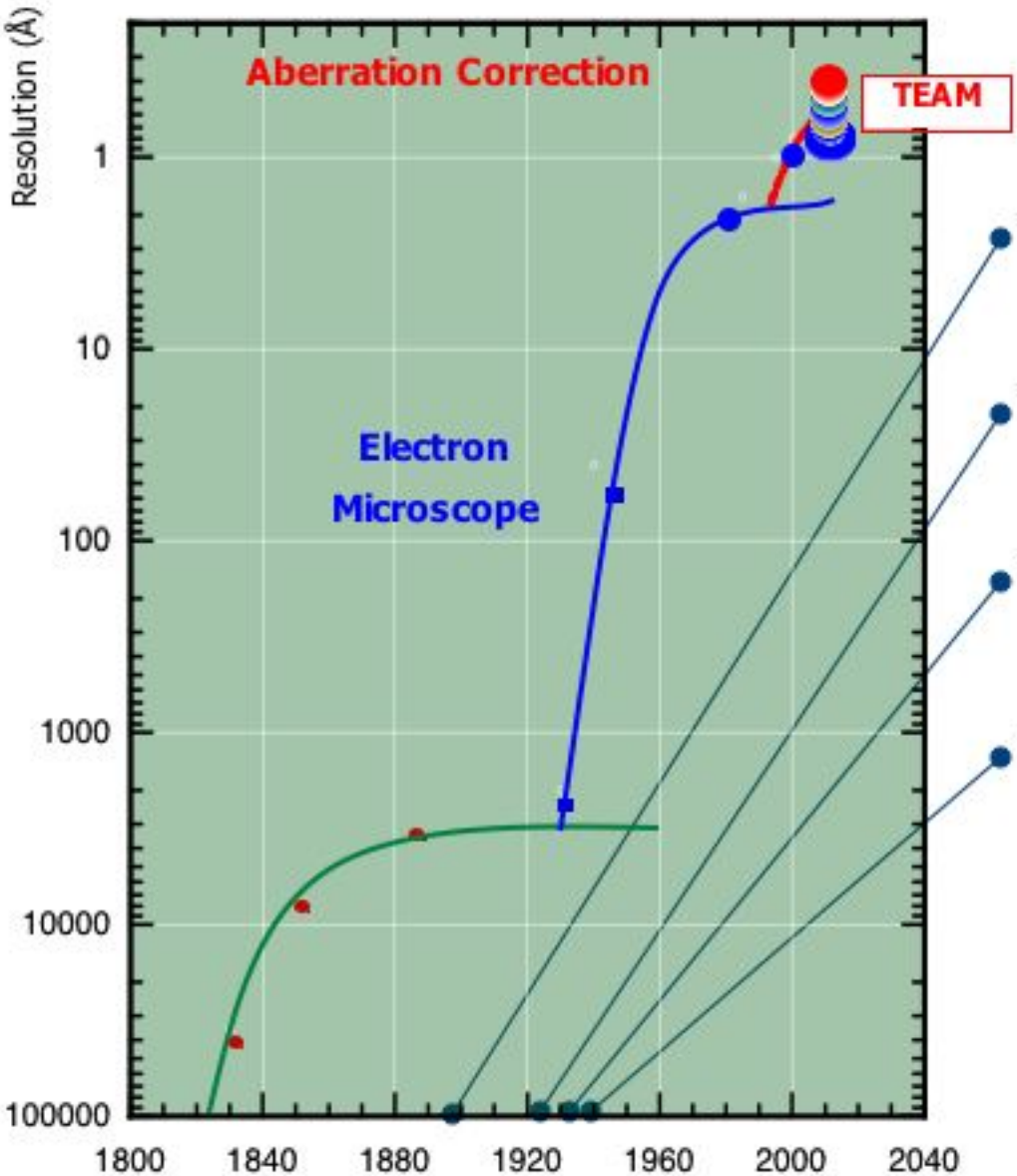
Why now?



- A breakthrough in electron optics removes the barrier that has limited the performance of the electron microscope since its invention.
- Simultaneous advances in computers, electronics, detectors,...
- Nanoscience and technology centers need atomic-level characterization.
- Aberration correction key to nanomaterials research.

Historical Perspective

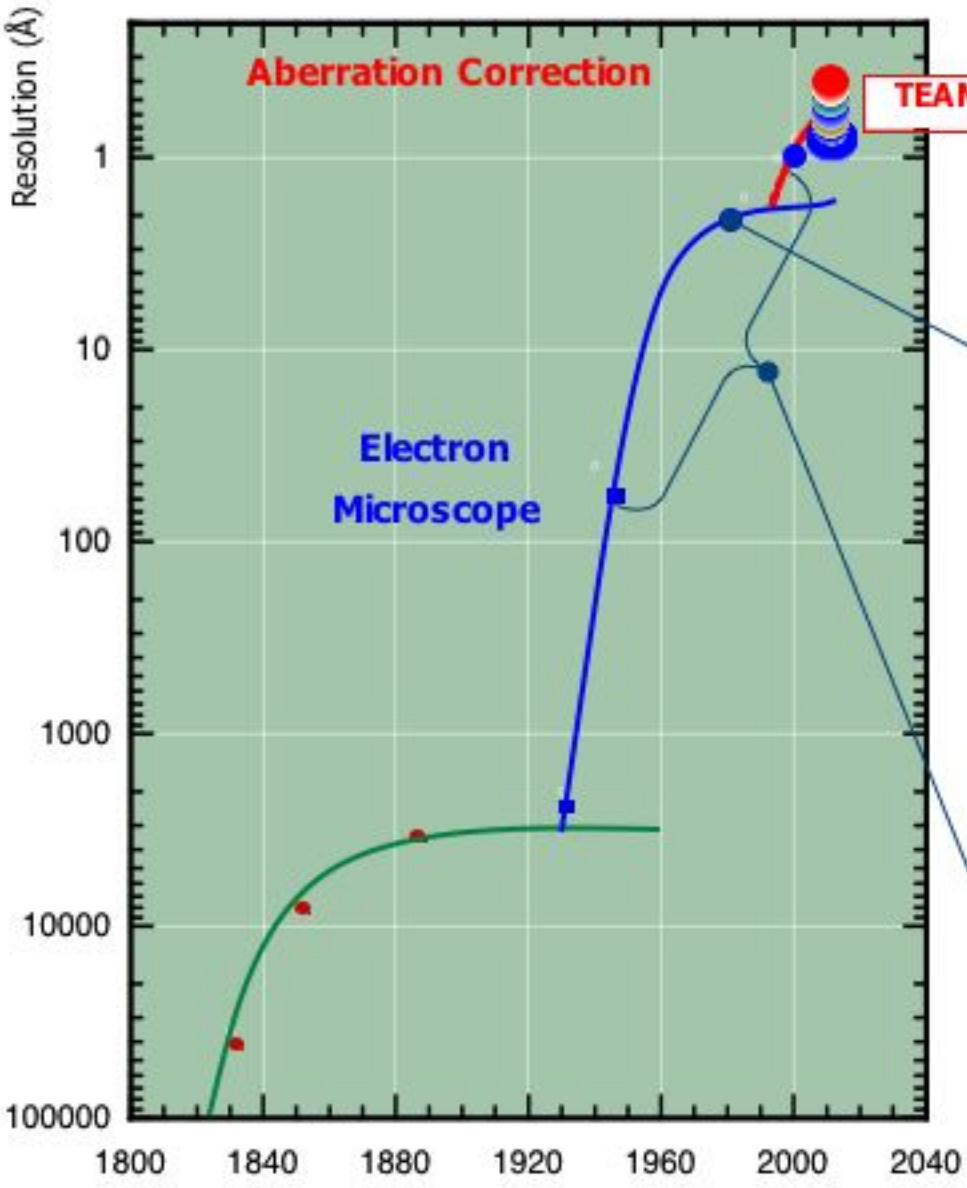
significant events

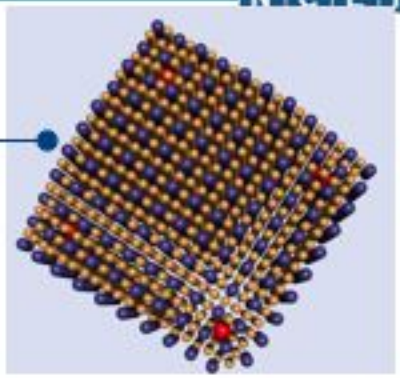


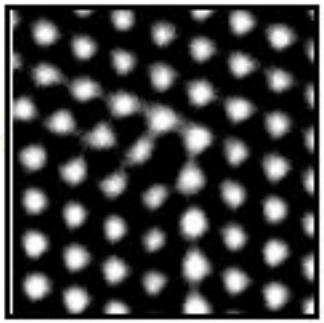
- 1897 Discovery of the electron - *Thompson*
- 1924 Wave nature of electrons - *de Broglie*
- 1932 Electron microscope - *Knoll, Ruska*
- 1939 First commercial TEM - *Siemens, Halske*

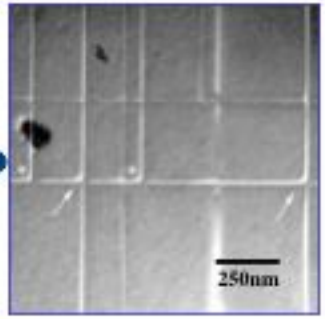
Historical Perspective

significant events





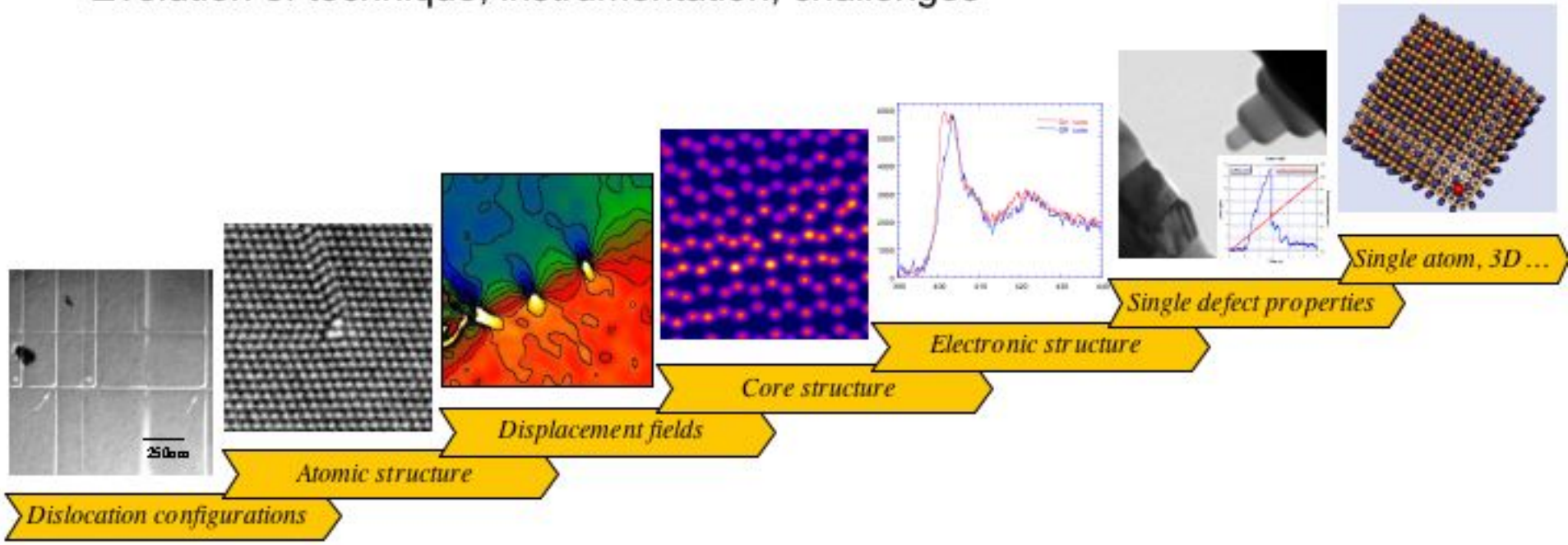




Defects in Materials

Recent history of TEM's growing role

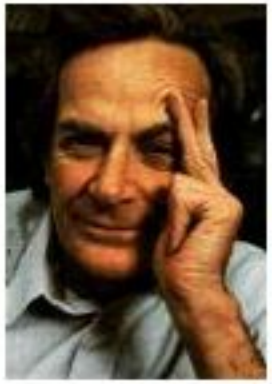
Evolution of technique, instrumentation, challenges



Diffraction contrast | Atomic resolution | Computing | Z-contrast | Spectroscopy | Dynamics | Aberration correction

Feynman's Challenge

"It would be very easy to make an analysis of any complicated chemical substance; all one would have to do would be to look at it and see where the atoms are. The only trouble is that the electron microscope is one hundred times too poor … I put this out as a challenge: Is there no way to make the electron microscope more powerful?"



– Richard P. Feynman, 1959,
"There's Plenty of Room at the Bottom"

TEAM Project

Transmission Electron Aberration-corrected Microscope

A collaborative project to develop the next-generation electron microscope.

Multiple partners, led by NCEM.
First instrument installed in Berkeley in December 2007.

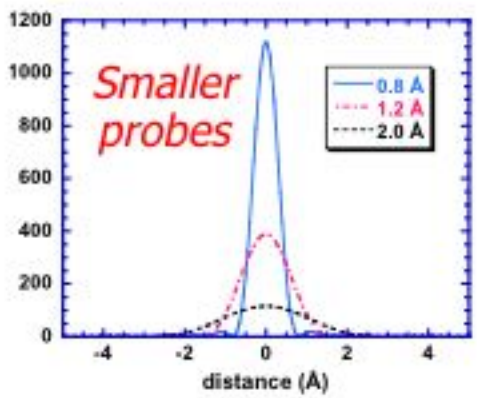
Unprecedented scientific opportunities for observing the atomic-scale order, electronic structure and dynamics of individual nanostructures …

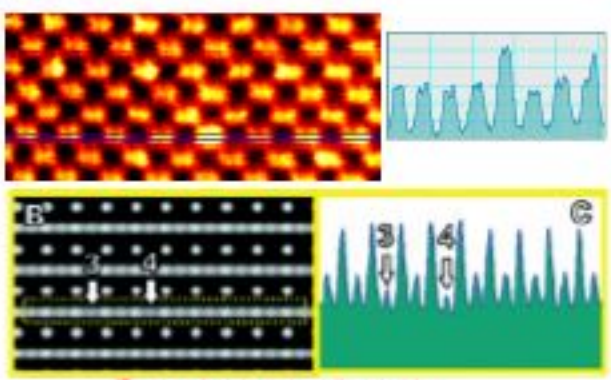
What Does Aberration Correction Buy?

Conventional electron microscopes: d ~100 λ

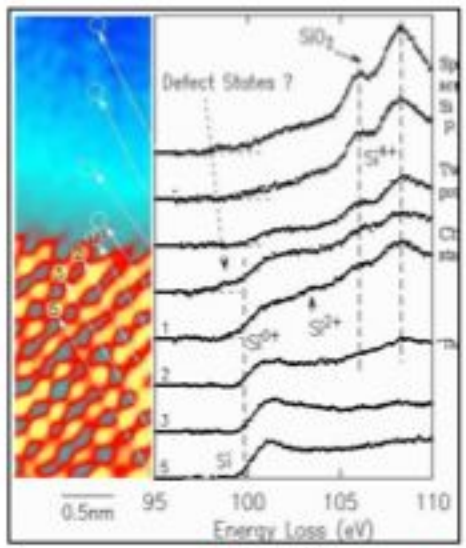
C_s- corrected electron microscopes: d ~40 λ

C_s+ C_c- corrected microscopes (TEAM): d ~20 λ

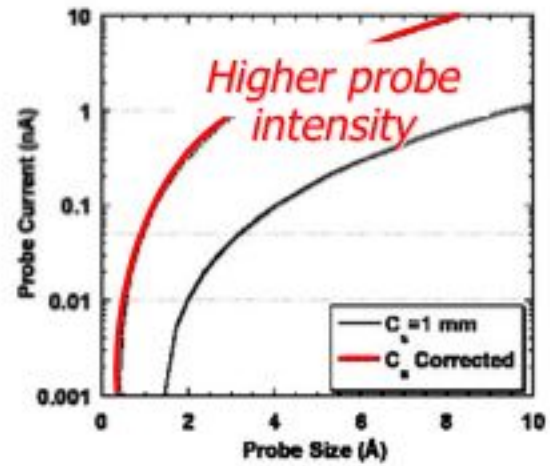


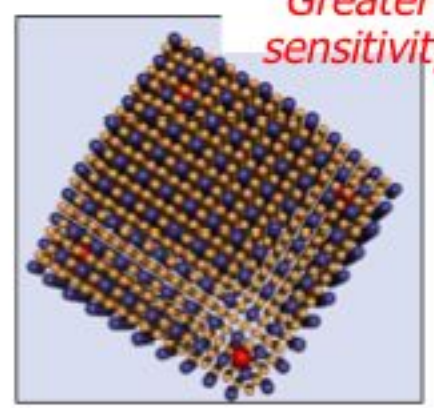


Greater contrast



More signal





Greater sensitivity

TEAM Background

Involvement of the scientific community

- 2000 Stringer BESAC Panel Review endorsement of TEAM "vision document"
- 1st TEAM Workshop at ANL July 2000
- 2nd TEAM Workshop at LBNL July 2002
- 3rd TEAM workshop
  - MSA San Antonio, August 2003
- 4th TEAM workshop / Focused Interest Group
  - MSA Savannah, August 2004
- In-situ TEAM workshop,
  - FS-MRL, Illinois, July 2005
- TEAM symposium
  - MSA Honolulu, August 2005
- MSA 2006, 2007, AVS 2007, MRS 2007 …

- Scientific Advisory Committee
  - *C.B. Carter, U Minnesota*
  - *J.A. Eades, Lehigh*
  - *J. Silcox, Cornell*
  - *J.C.H. Spence, ASU*
  - *R. Tromp, IBM*

http://www.lbl.gov/LBL-Programs/TEAM/index.html

WORKSHOP REPORT

ABERRATION CORRECTION IN ELECTRON MICROSCOPY

MATERIALS RESEARCH IN AN ABERRATION-FREE ENVIRONMENT

REPORT

SECOND TEAM WORKSHOP

MATERIALS RESEARCH IN AN ABERRATION-FREE ENVIRONMENT

July 18 - 19, 2002
Lawrence Berkeley National Laboratory

REPORT

Third TEAM Workshop

Materials Research in an Aberration-Free Environment

2004 Focused Interest Group

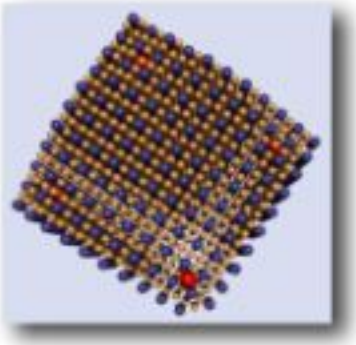
2004 Focused Interest Group
Pre-Congress Meeting

REPORT

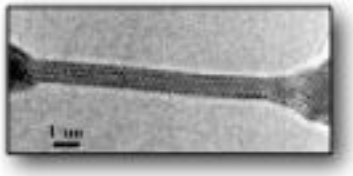
Materials Research in an Aberration-Free Environment

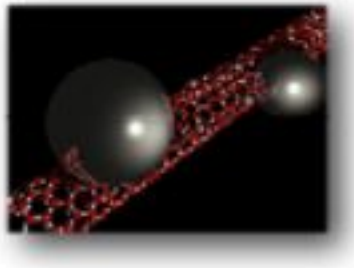
TEAM is Driven by Scientific Needs

Extraordinary scientific opportunities by direct observation of individual nanostructures



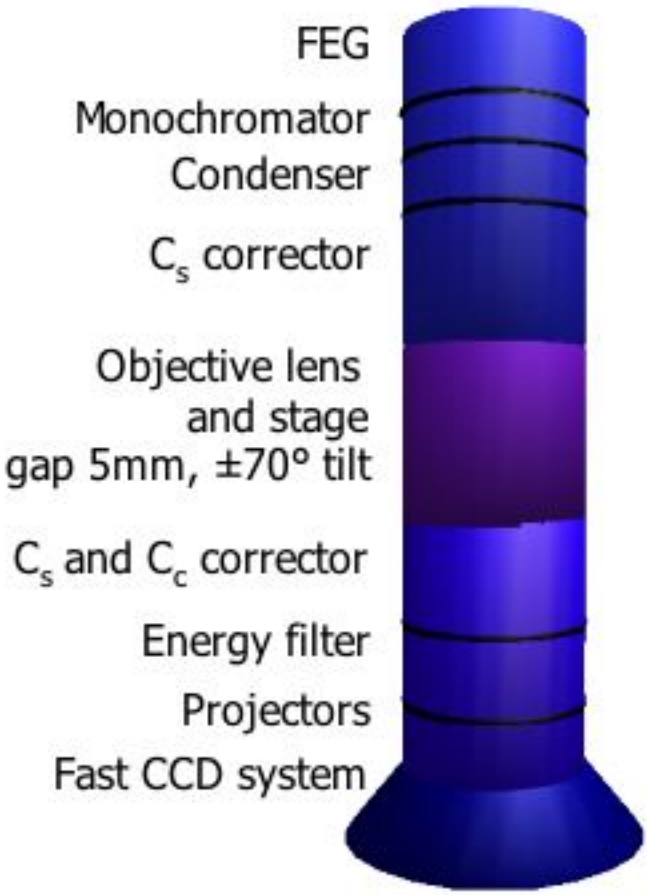
- three-dimensional atomic-scale structure, shape, and defect distribution
- spectroscopic identification and location of individual dopant atoms
- direct imaging of the atomic-scale structure of glasses
- electronic structure of individual point defects
- non-spherical charge density and valence electron distribution
- in-situ synthesis of novel nanoscale structures
  - e.g., electron-beam lithographic removal of atomic columns
- in-situ observation of properties and response to external variables
  - temperature, stress, chemical activity, and applied electric and magnetic fields…





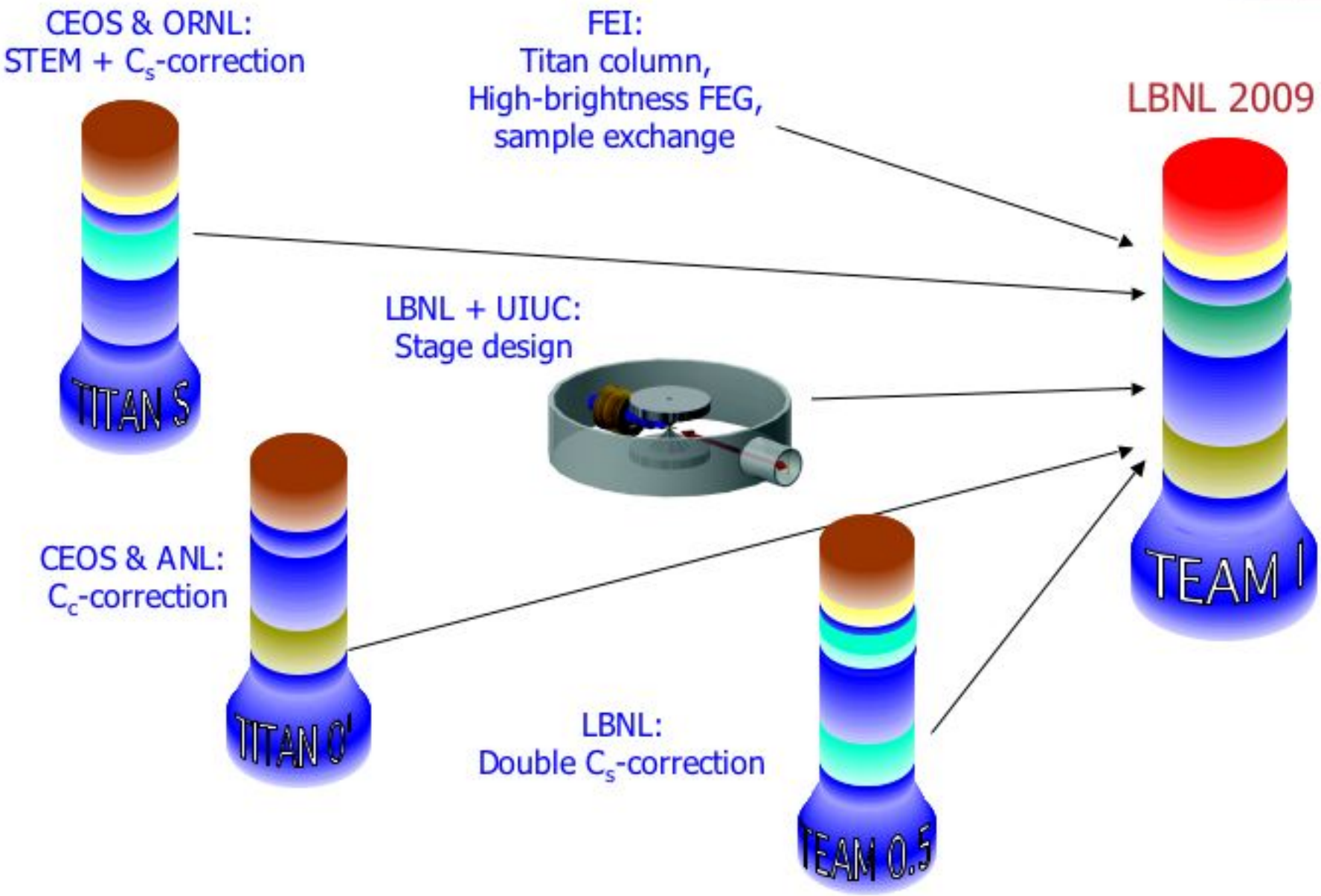
… all with unprecedented spatial, spectral & temporal resolution

The TEAM Instrument



Parallel Technological Developments

stepwise integration 2006-09

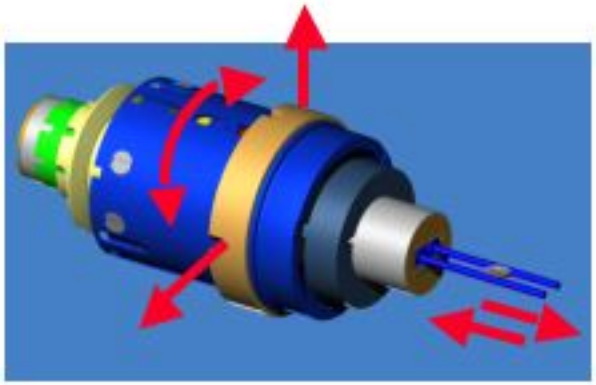


TEAM Stage

5-axis, in-column, piezo-stage

A. Schmid, T. Duden, NCEM + E. Olson I. Petrov, FS-MRL UIUC

- Design inspired by AFM
- Small, high stiffness, high resonance frequency
- Piezo-controllers
- No link to environment



Capacitive Position Sensing

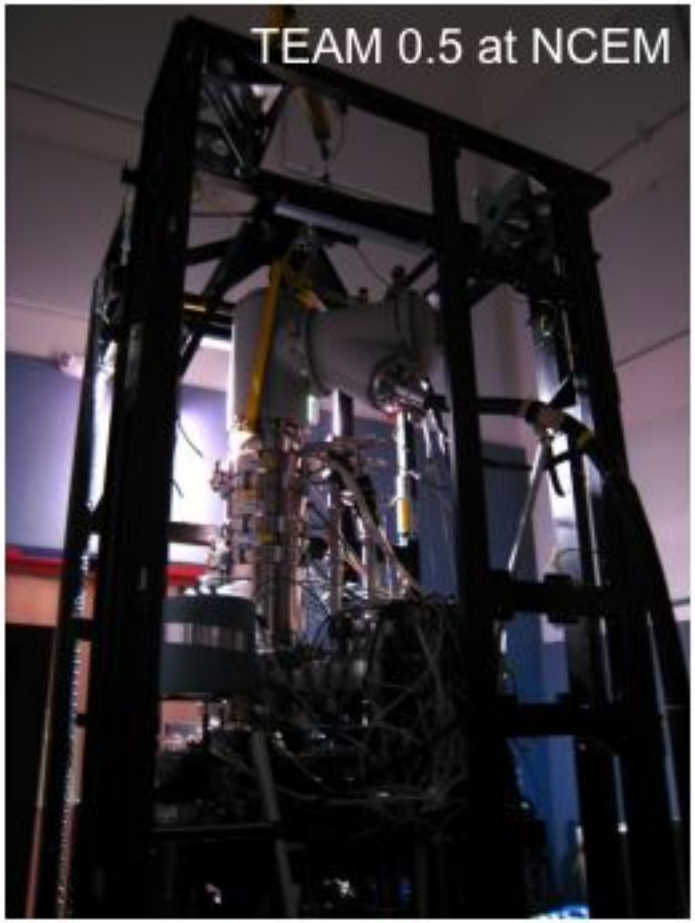
- Absolute measurement
- No 'homing' necessary.
- Precision to a few nm

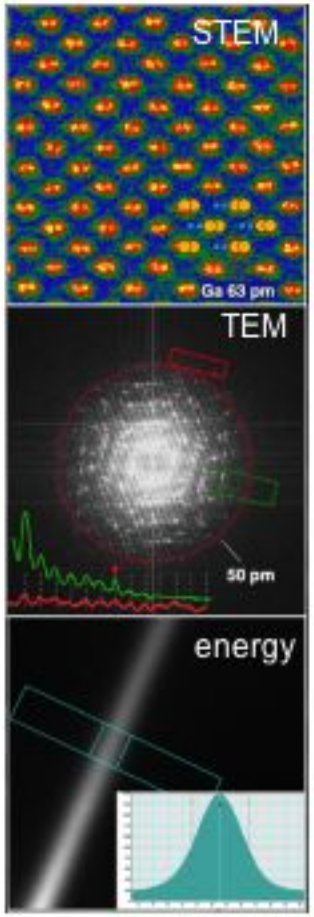
Enabling special experiments

- Tomography
- Focal series
- Sample scan
- Spectroscopy
- Low-dose …

TEAM on Track

a whistlestop on DOE's Roadmap for the Future of Science…



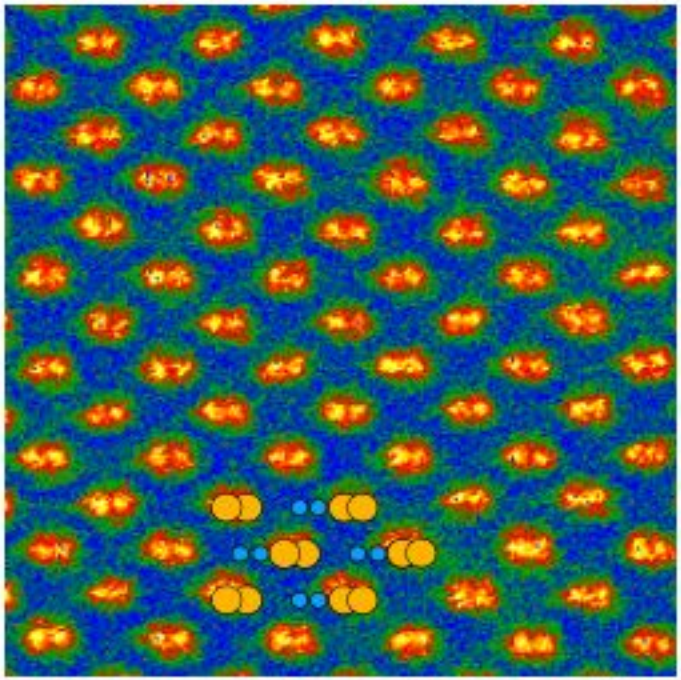


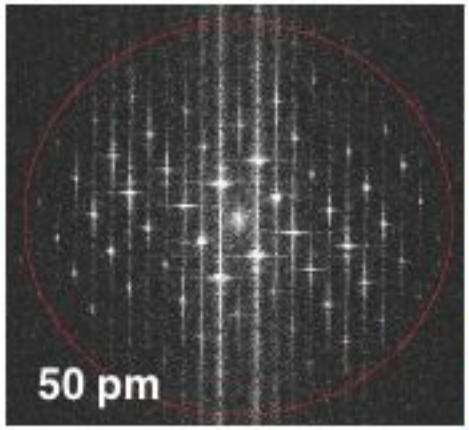
TEAM is a small project but important in the big picture of DOE plans for the future of science.

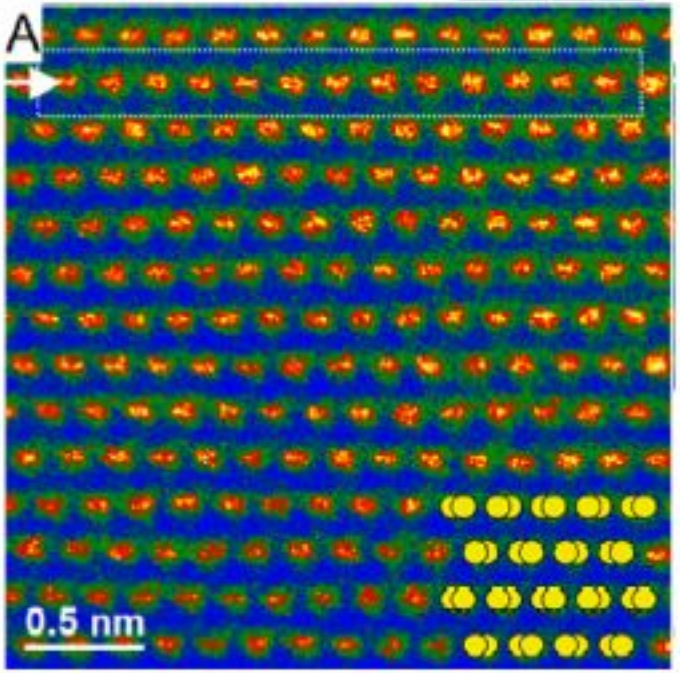
TEAM 0.5 has met its major milestones ahead of schedule -

- 0.5Å information transfer in TEM and STEM,
- 0.1eV energy spread.

TEAM 0.5 Performance in STEM



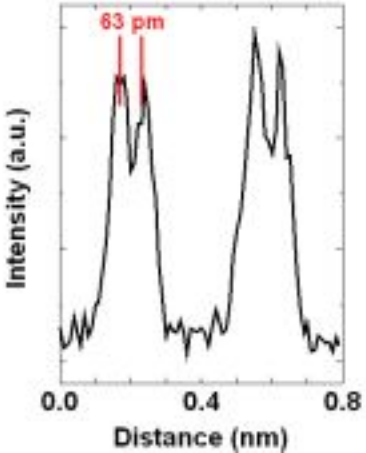


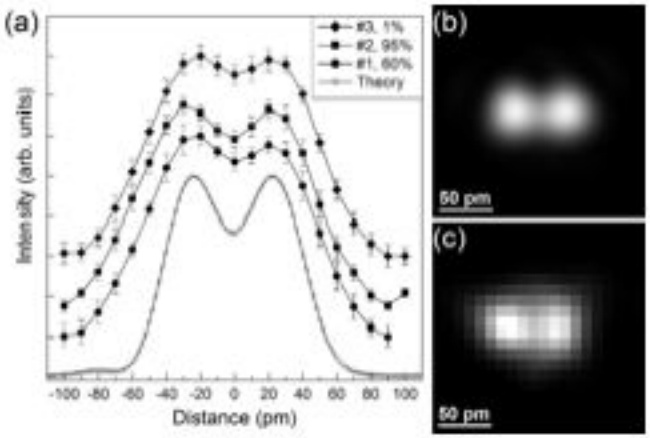


GaN 112 63pm

Ge 114 47pm

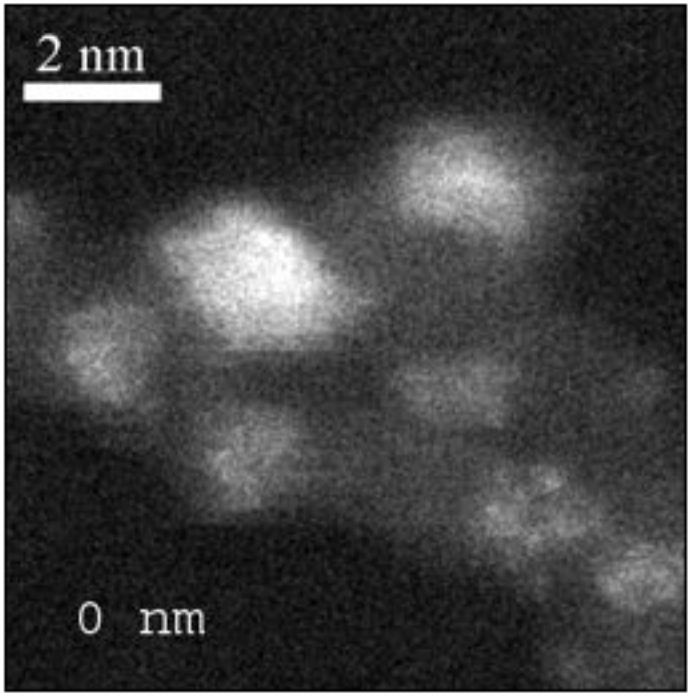
R. Erni



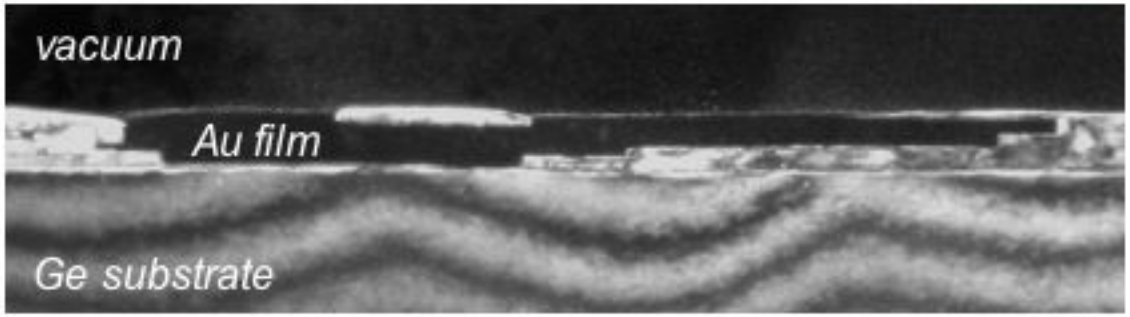


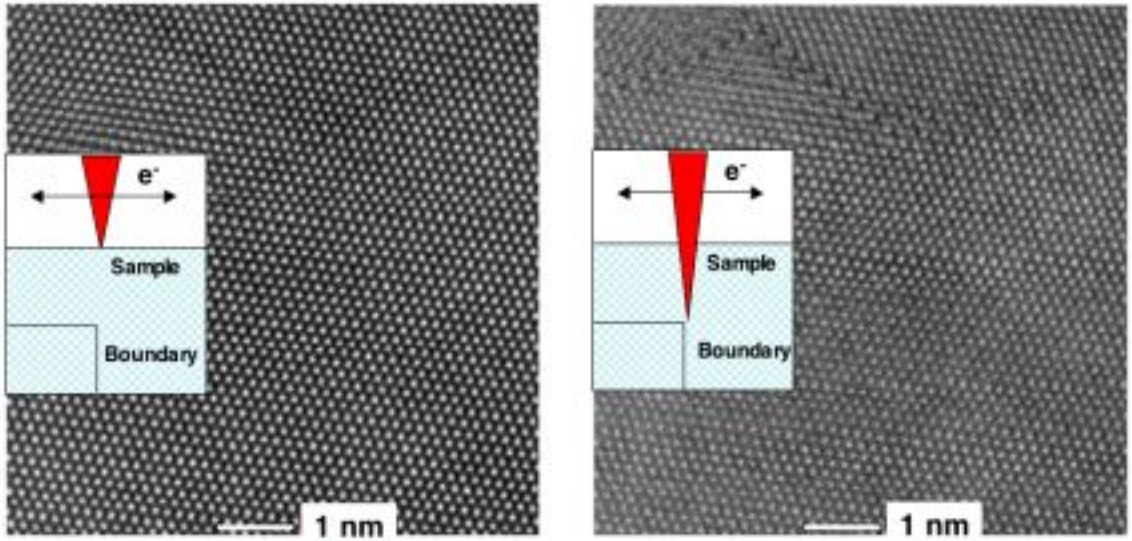
Depth Sectioning Tomography

Convergence angle reduces depth of focus



HAADF depth series of (Pt, Ru) catalyst on γ-Al_2O_3.





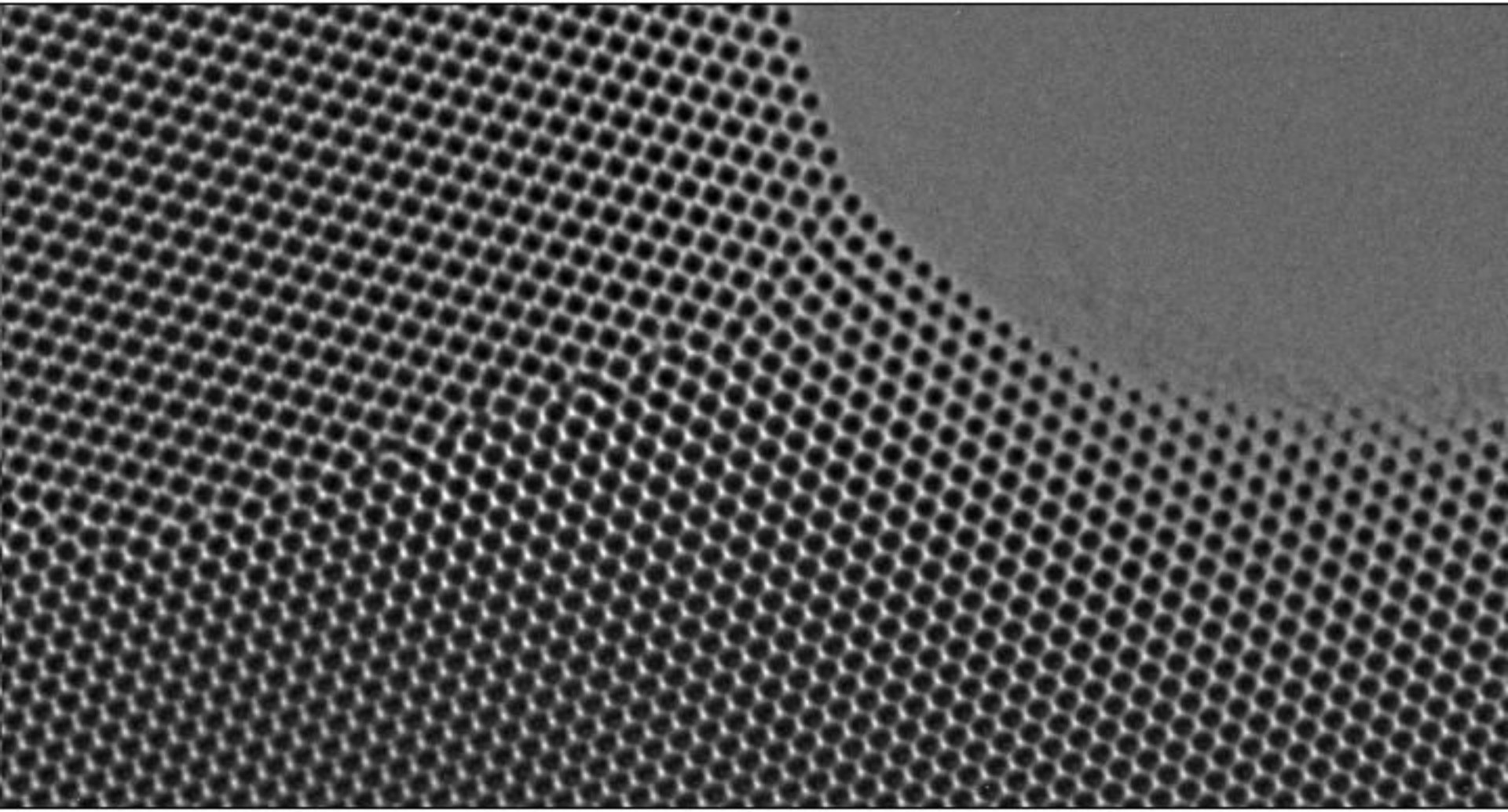
Imaging a buried interface in Au bicrystal - TEAM 0.5

Borisevic, Lupini, Pennycook, PNAS 2006
Nellist et al. APL 2006

Kisielowski, Erni, van Lin et al.

TEAM 0.5

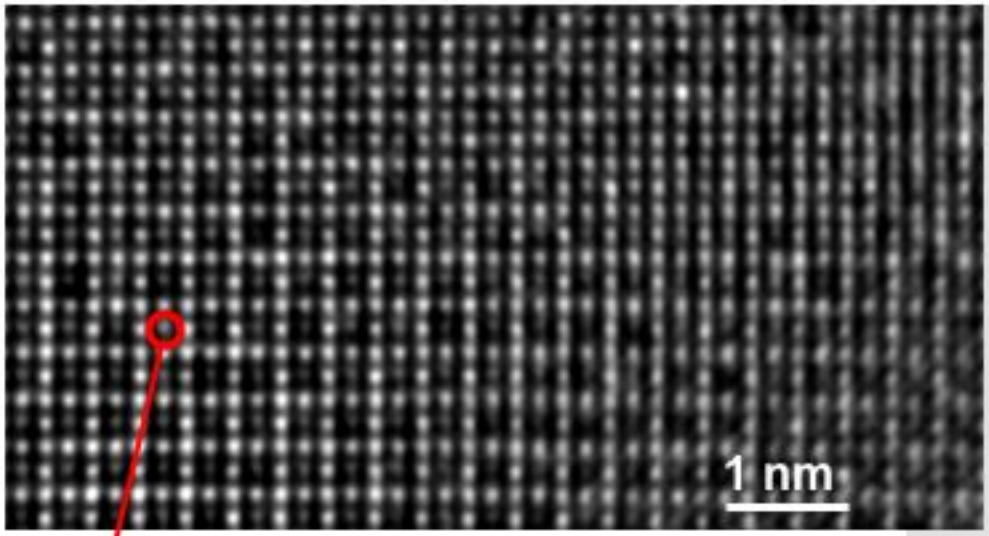
atomic structure of 90° <110> tilt boundary in Au

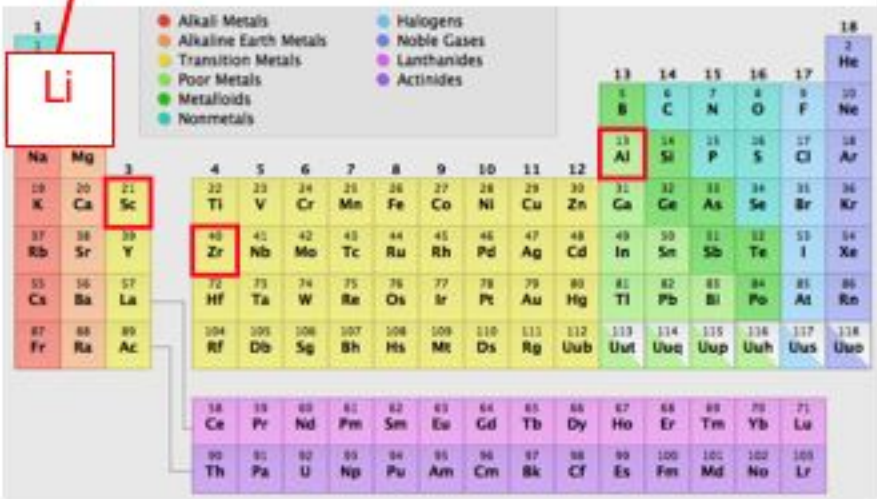


Resolving Li in Al-(Li,Sc,Zr) Alloy

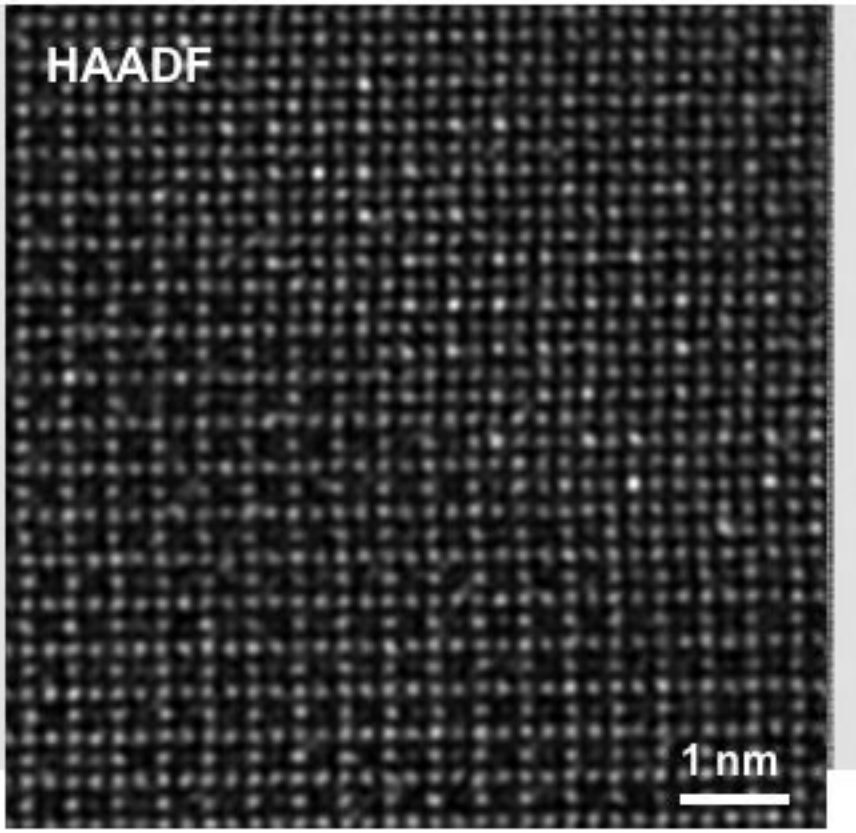
V. Radmilovic, M. Rossell, R. Erni

TEM phase of exit wave



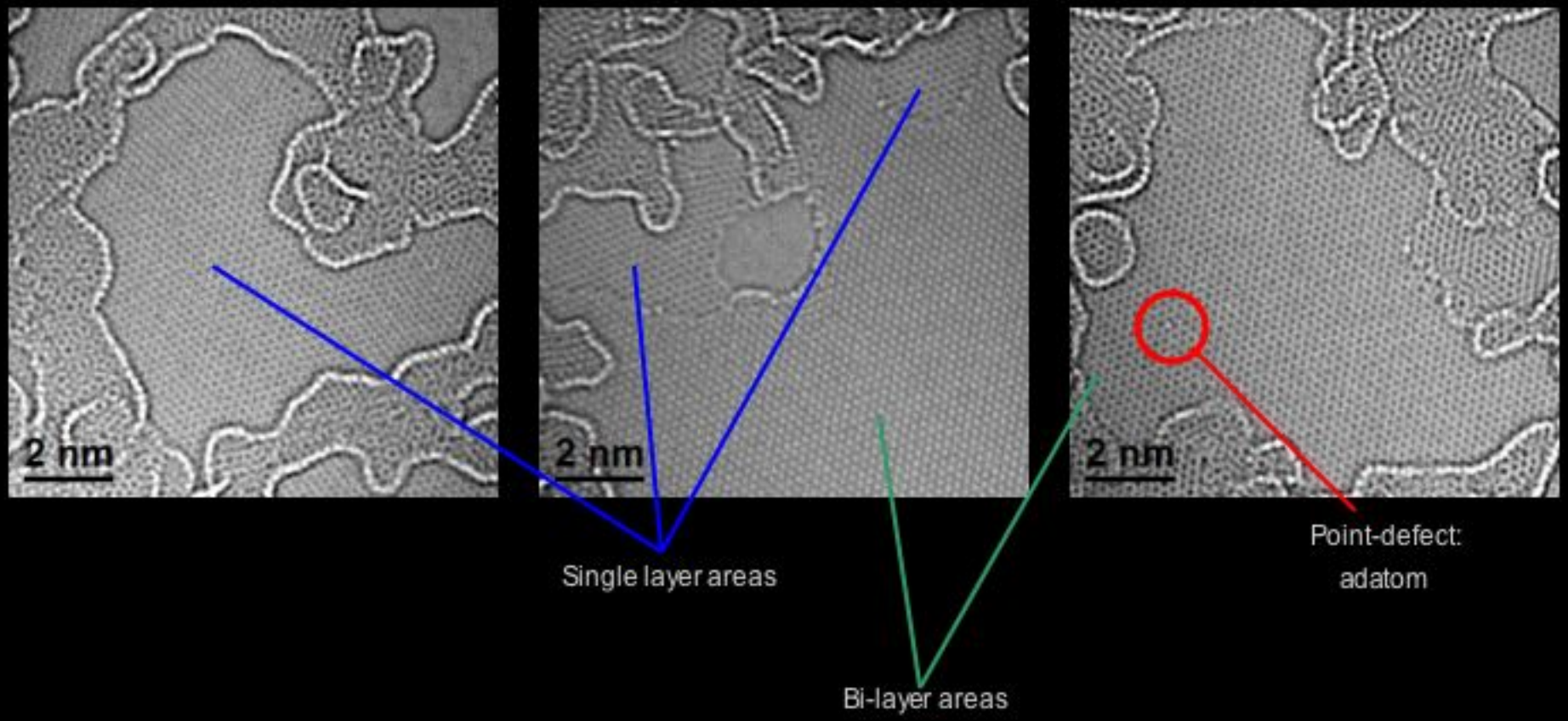


STEM focal series



- TEAM 0.5 resolves Li atoms in core-shell precipitates in TEM mode,
- Sensitivity to Sc, Zr and depth resolution in STEM mode.

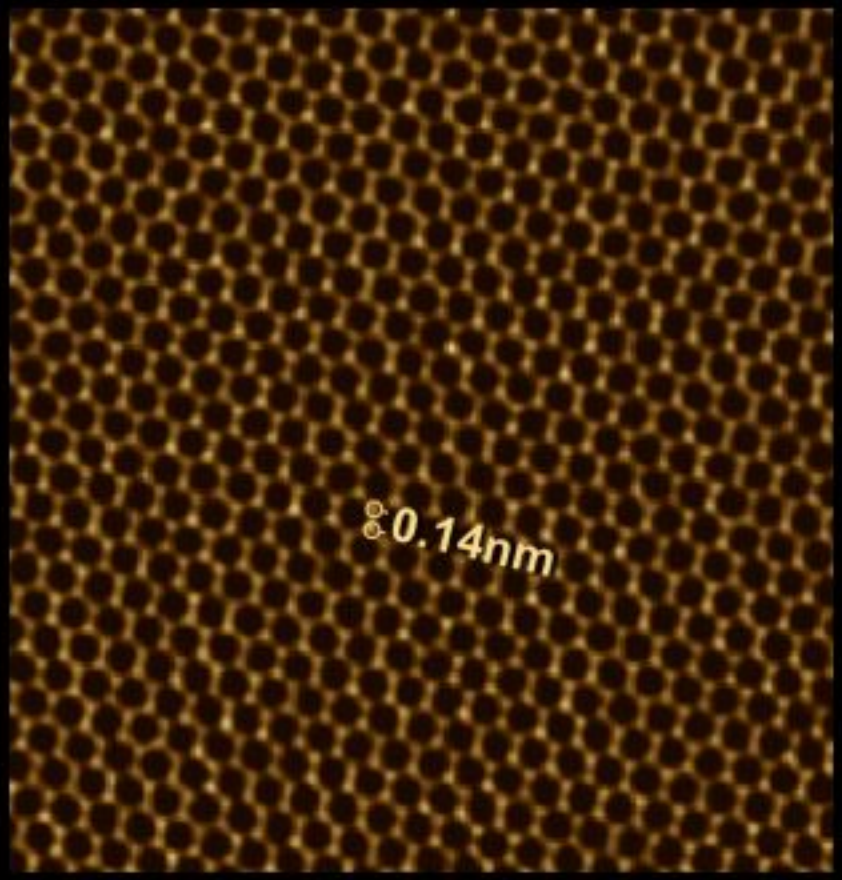
Single and bi-layer graphene



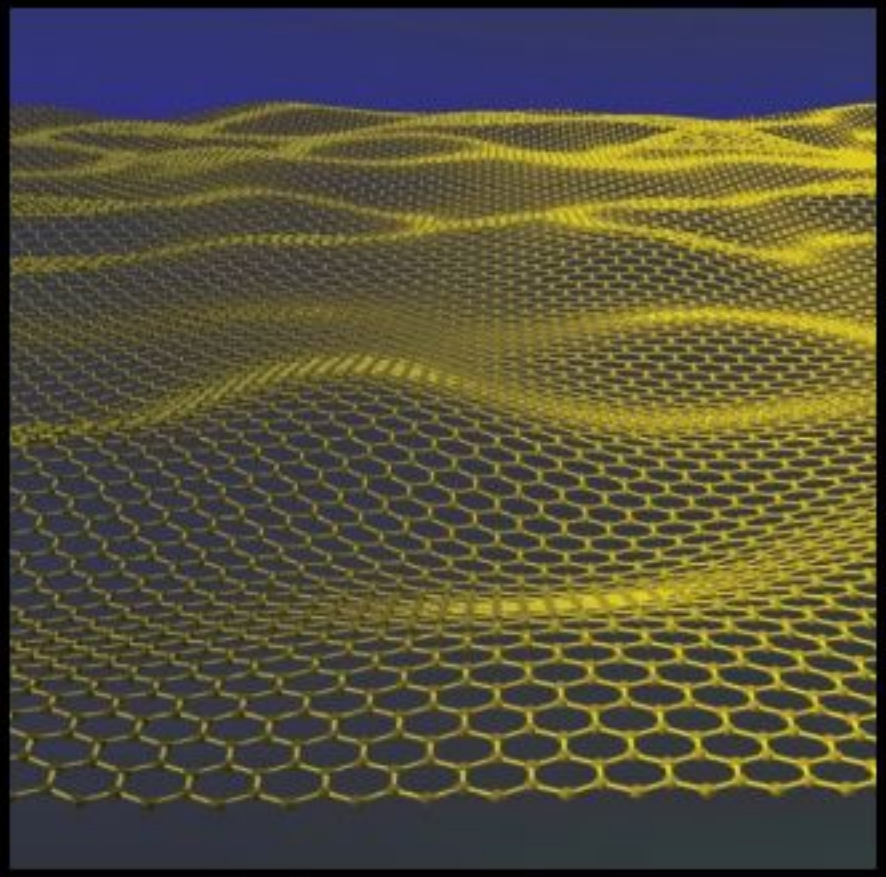
J. Meyer, R. Erni,
C. Kisielowski, 2008

TEAM 0.5

graphene sheets



TEAM 0.5



model

80 kV, monochromator
C_a = - 0.015 µm, C_s = 5 mm
Information limit < 0.1 nm

J. Meyer, R. Erni,
C. Kisielowski, 2008

Workshop Issues

TEAM is meeting performance goals and is on track to open for user operations.

- Opportunities and scenarios for research via remote access to TEAM.
- Individual experience/interest in remote operation.
- Compatibility of remote control with different techniques of microscopy.
- Software, hardware and support requirements.
- Overview ESnet.