U.S. DEPARTMENT OF ENERGY | Office of Science

The many uses of Synchrotrons

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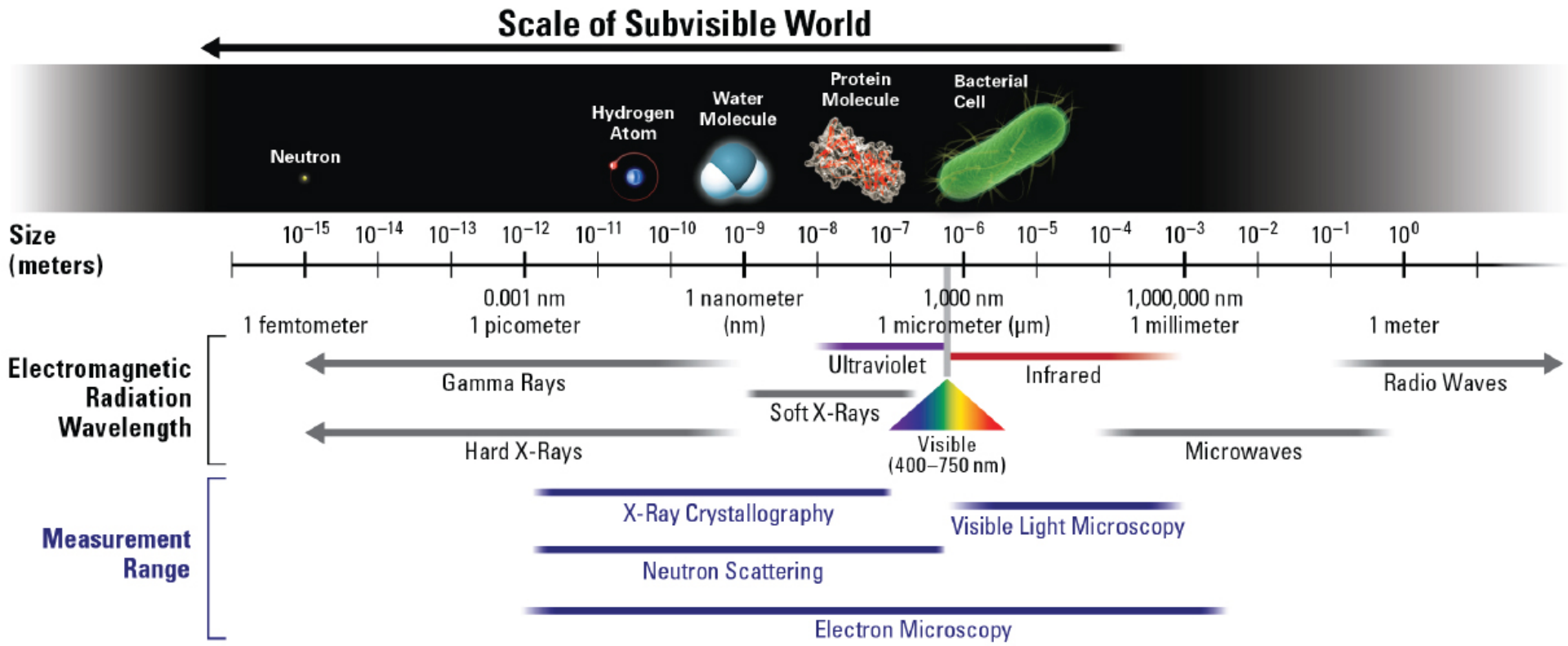
Director of the Office of Science
U.S. Department of Energy

San Diego
November 8, 2012

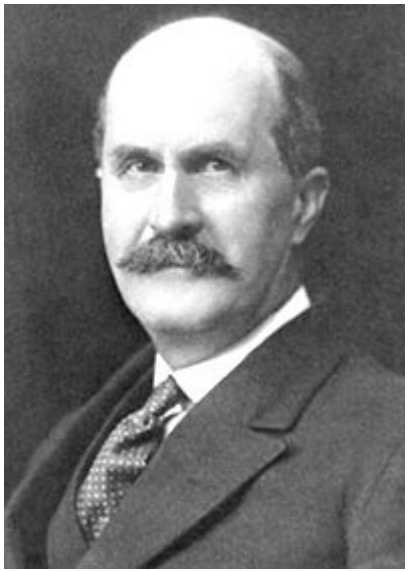
Rontgen wife ‘s hand(1895)

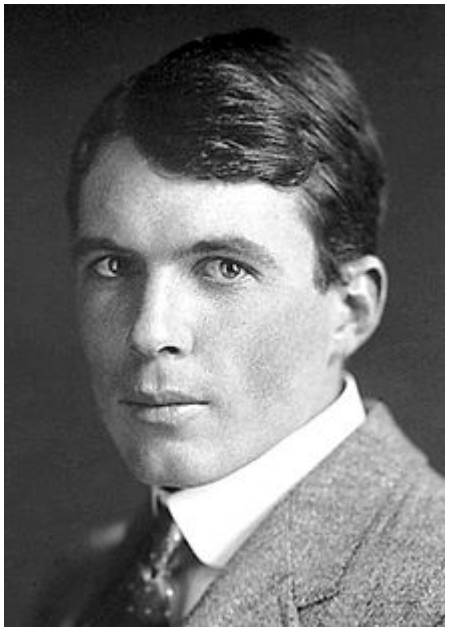
First Nobel Prize 1901

Motivation: Seeing Matter at Atomic & Molecular Scales



William Henry Bragg and William Lawrence Bragg

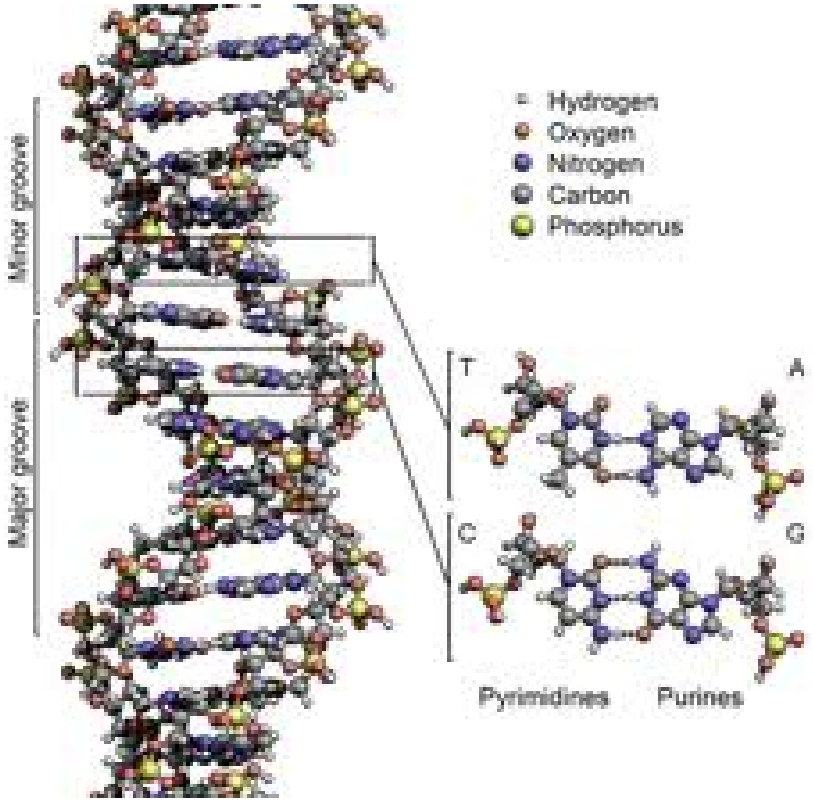




Nobel in Physics 1915 for Determining Crystal Structures
of in organic crystals-today data base with over 70,000 structures

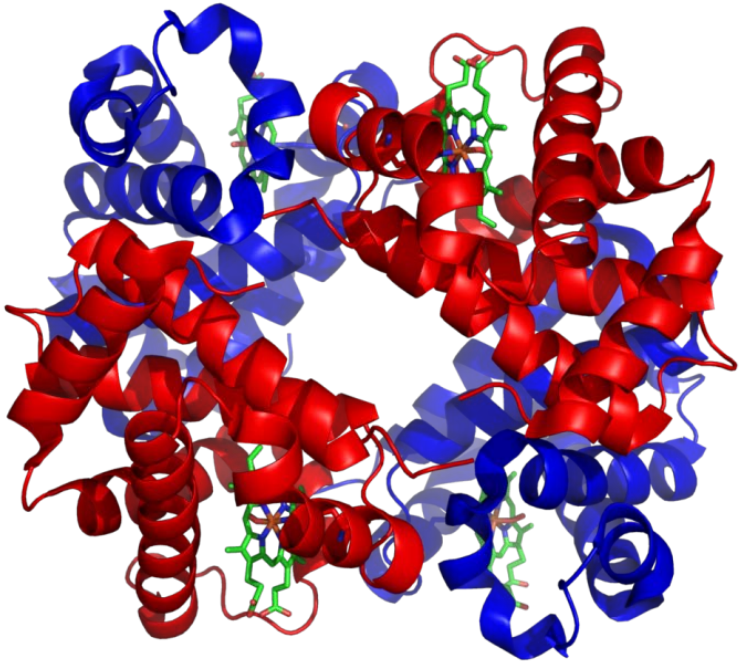
Shoe Fitting Fluoroscope

Watson and Crick 1953 Structure of DNA



Nobel Prize in medicine 1962

Hemoglobin Structure was solved in the Fifties by Perutz



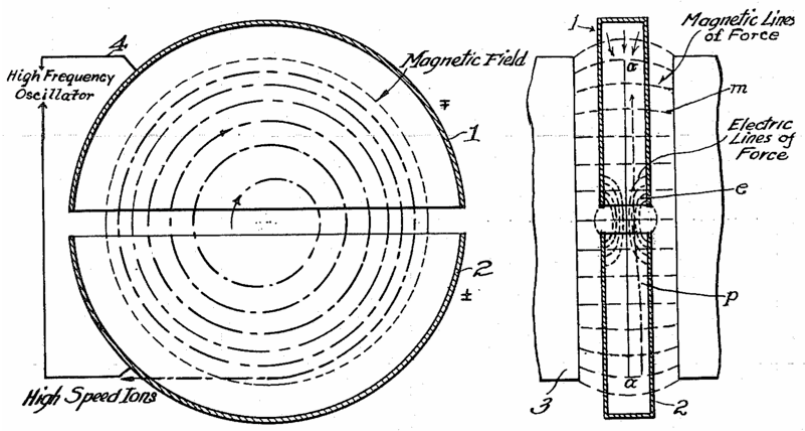
Nobel Prize in Chemistry in 1962

Particle physics motivated early efforts to accelerate protons and electrons.

Early accelerators:

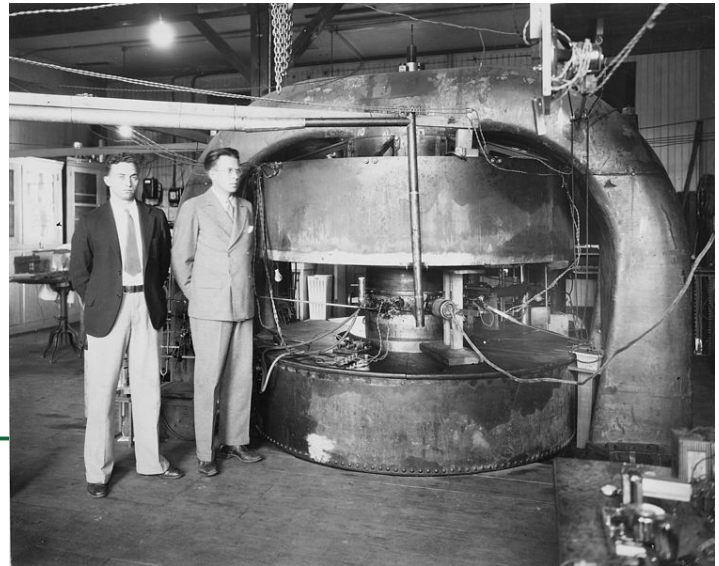
- **Linear accelerator**: Simple process: create a large voltage and accelerate a proton or electron across the electric field) (Crockroft/Walton)

- **Cyclotron**: Accelerate electron across a narrow voltage gap, keep electrons over the gap by applying a magnetic field, accelerating the electron repeatedly.

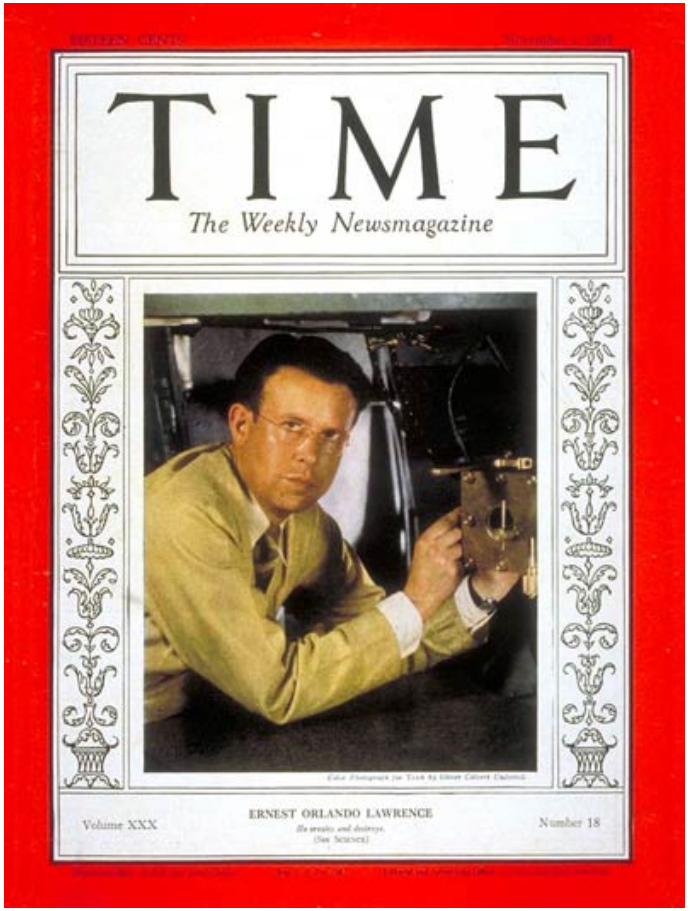


Above: Patent drawing for first Cyclotron (E.O. Lawrence.)

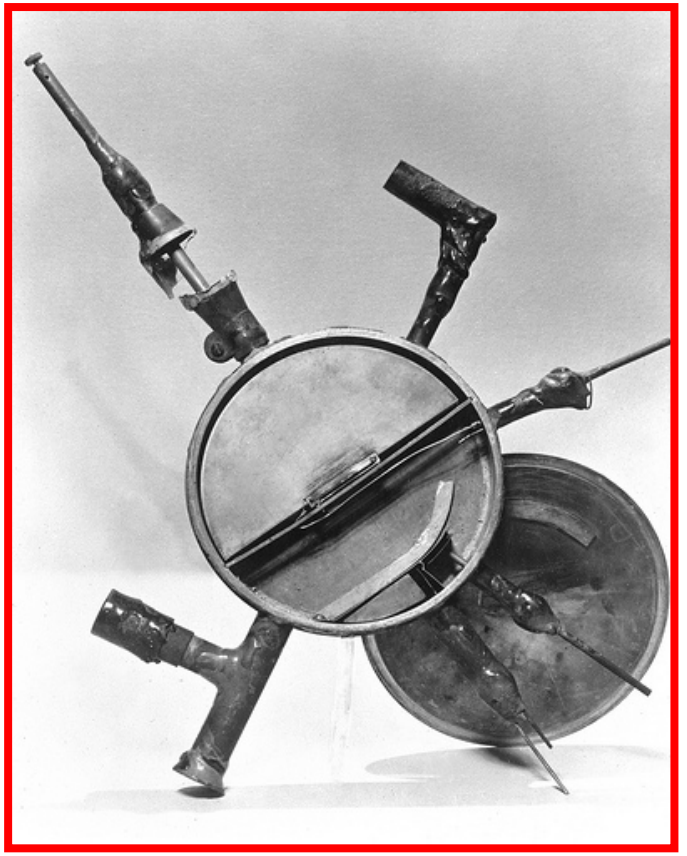
Right: E.O. Lawrence and an early Cyclotron



E.O. Lawrence and the Cyclotron

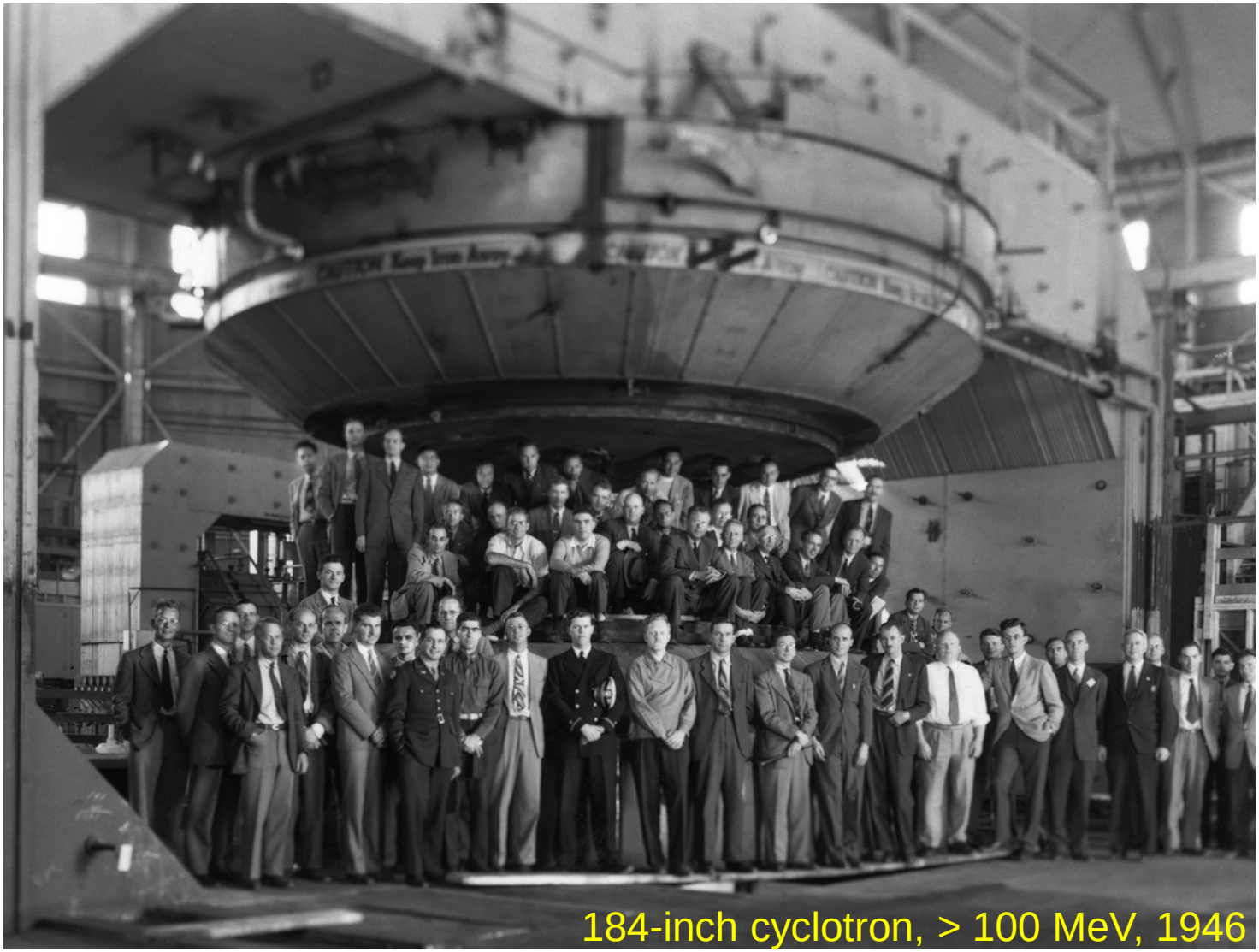


Ernest O. Lawrence
November 1, 1937



Lawrence's original
5-inch cyclotron, 80 keV, 1931

After several intermediate sizes came the 184-inch cyclotron …



184-inch cyclotron, > 100 MeV, 1946

... housed in its own designer building at LBNL , c 1941.

The building to house the 184-inch cyclotron was designed by Arthur Brown, whose works included San Francisco's City Hall, Opera House, and Coit Tower. (1941)

D. W. Kerst and the Betatron - 1941

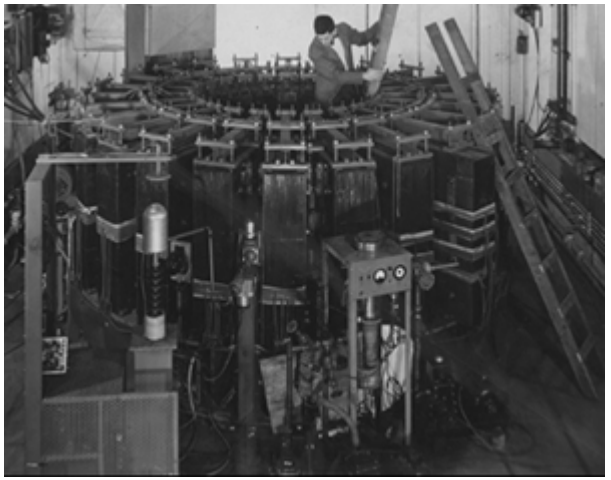
In a Betatron, Electrons in a fixed radius are accelerated by a changing magnetic field, which produces radiation. **Synchrotron Radiation** is the name for radiation from an accelerated electron in a circular motion. The betatron was used to generate x-rays for x-ray lithography and other purposes.

The Synchrotron

•Increase the magnetic field *in synchronization* with the increasing electric field, keeping the particles in a circular orbit of fixed radius. (No spiral outward like the cyclotron)

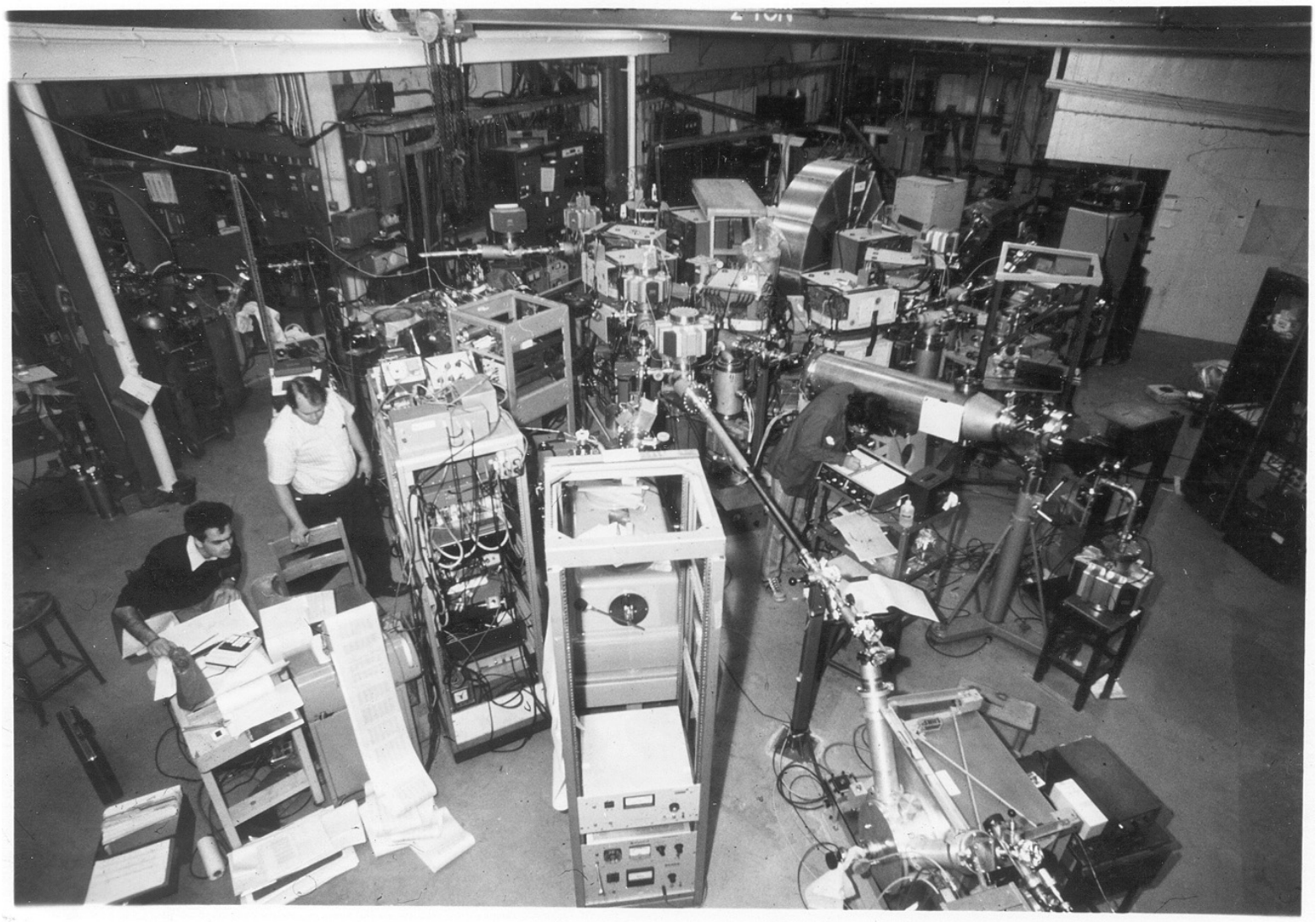
•First electron synchrotron was a modified betatron (1946)
•Synchotron technique further developed by creating an electron *storage ring* that could contain high-energy electrons

1947 GE Synchrotron Vacuum tube

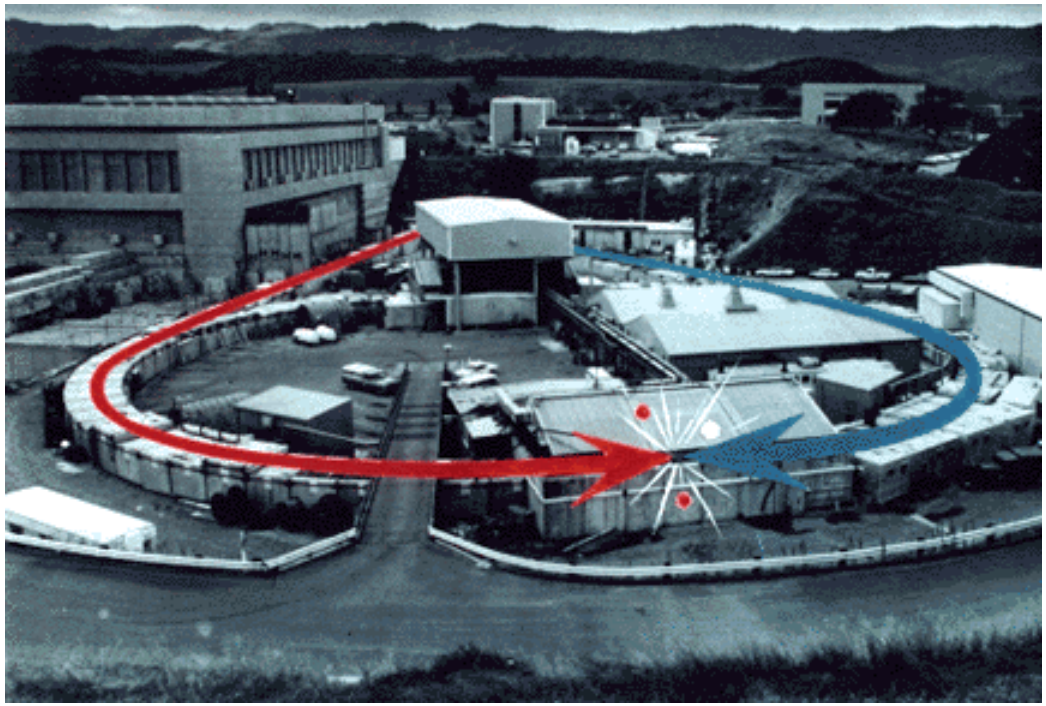


300 MeV Synchrotron at MIT (1962)

Tantalaus – Synchrotron with Storage ring. U. Wisconsin

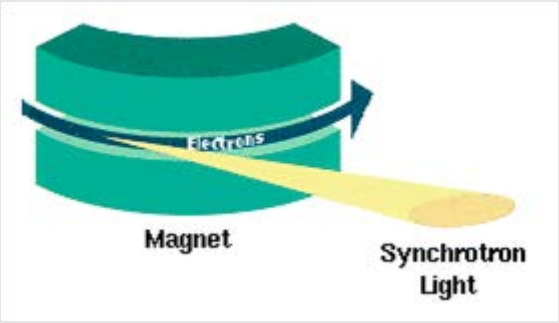


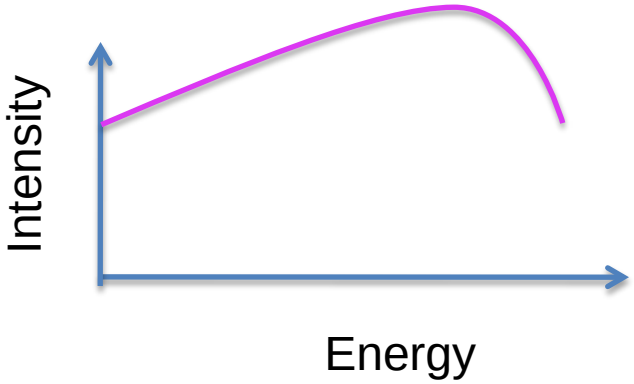
Colliding Beam Storage Ring at SLAC



Two important discoveries, J/psi and Tau lepton
Synchrotron Radiation was regarded as a nuisance

Synchrotron Radiation





Broadband radiation orders of magnitude more intensity than conventional sources from Ultra violet to hard x rays

Early Experiments

EUV Photoemission from crystals – electronic structure

Extended X ray Absorption Fine Structure- local configuration of atoms

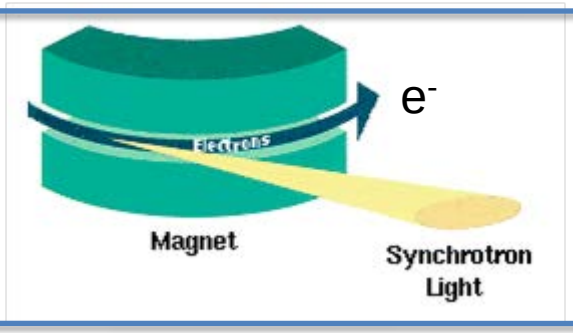
Surface X ray scattering- surface structure

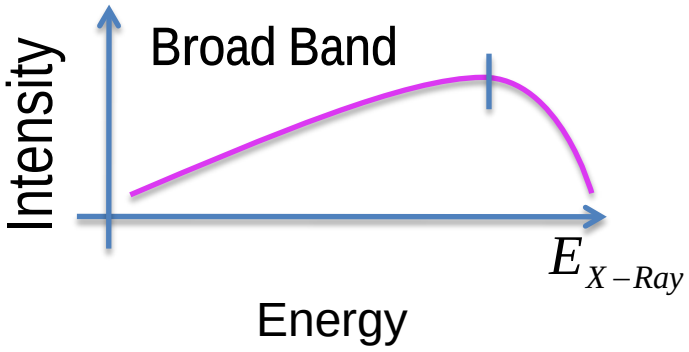
Crystallography of both organic and inorganic compounds

How to Produce X-rays: Accelerate Electrons in a Magnetic Field

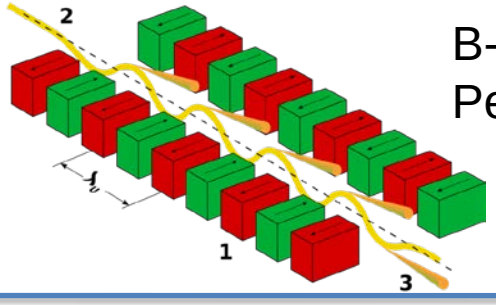
Synchrotron Radiation

Uniform B-Field

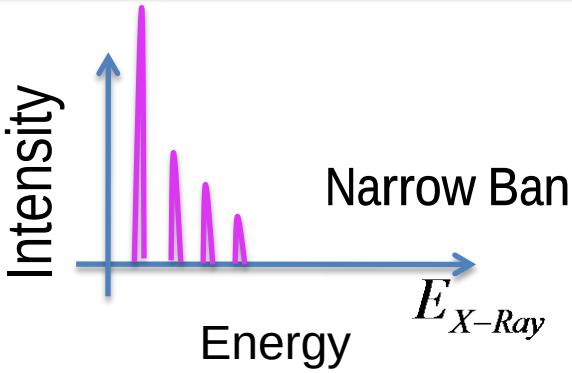




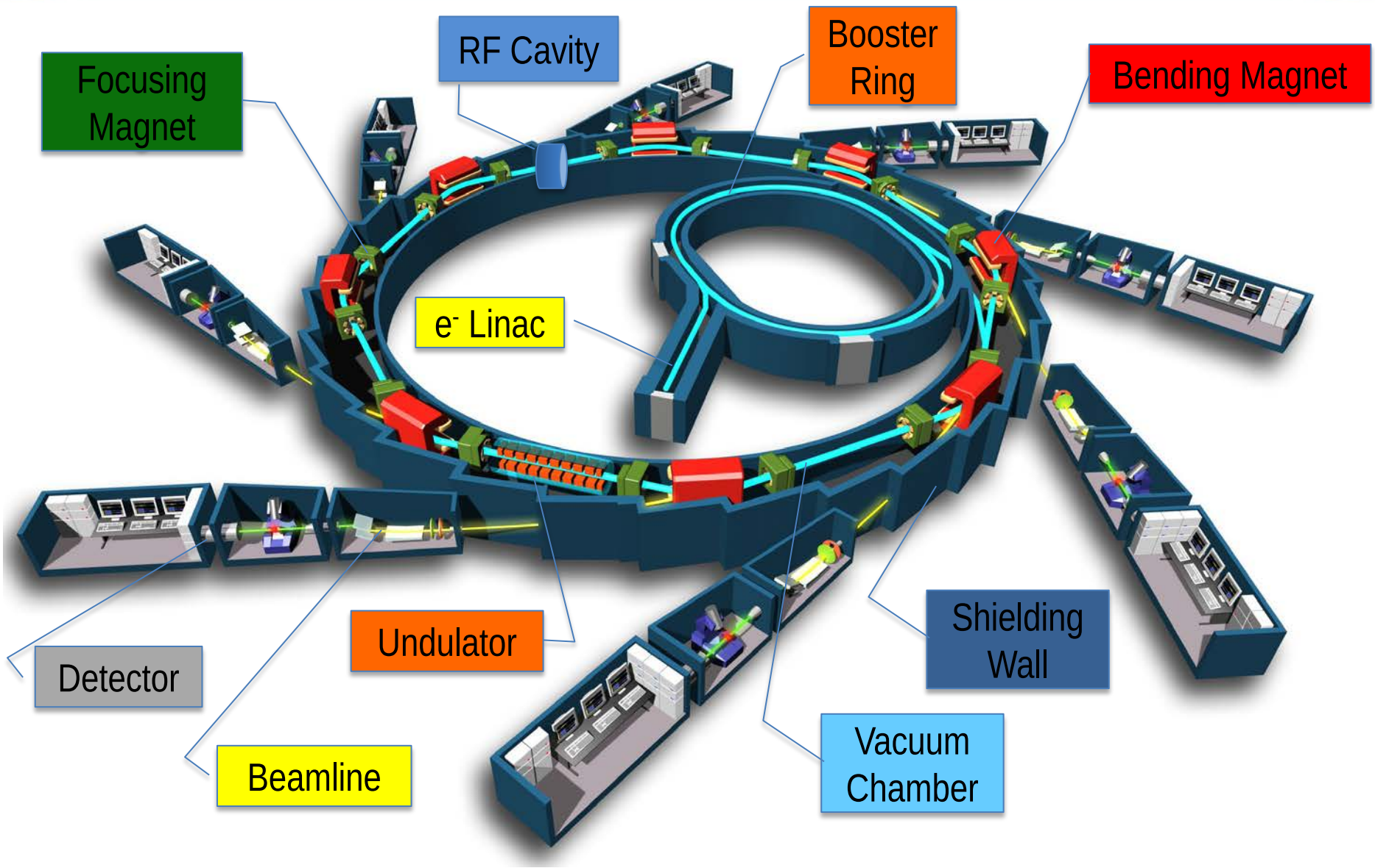
Undulator Radiation



B-Field with Period λ_u

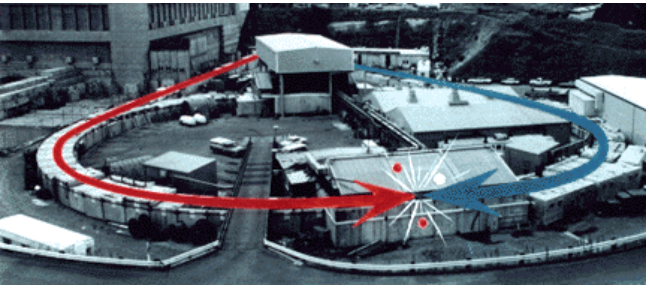


Layout of a Storage Ring Synchrotron Light Source



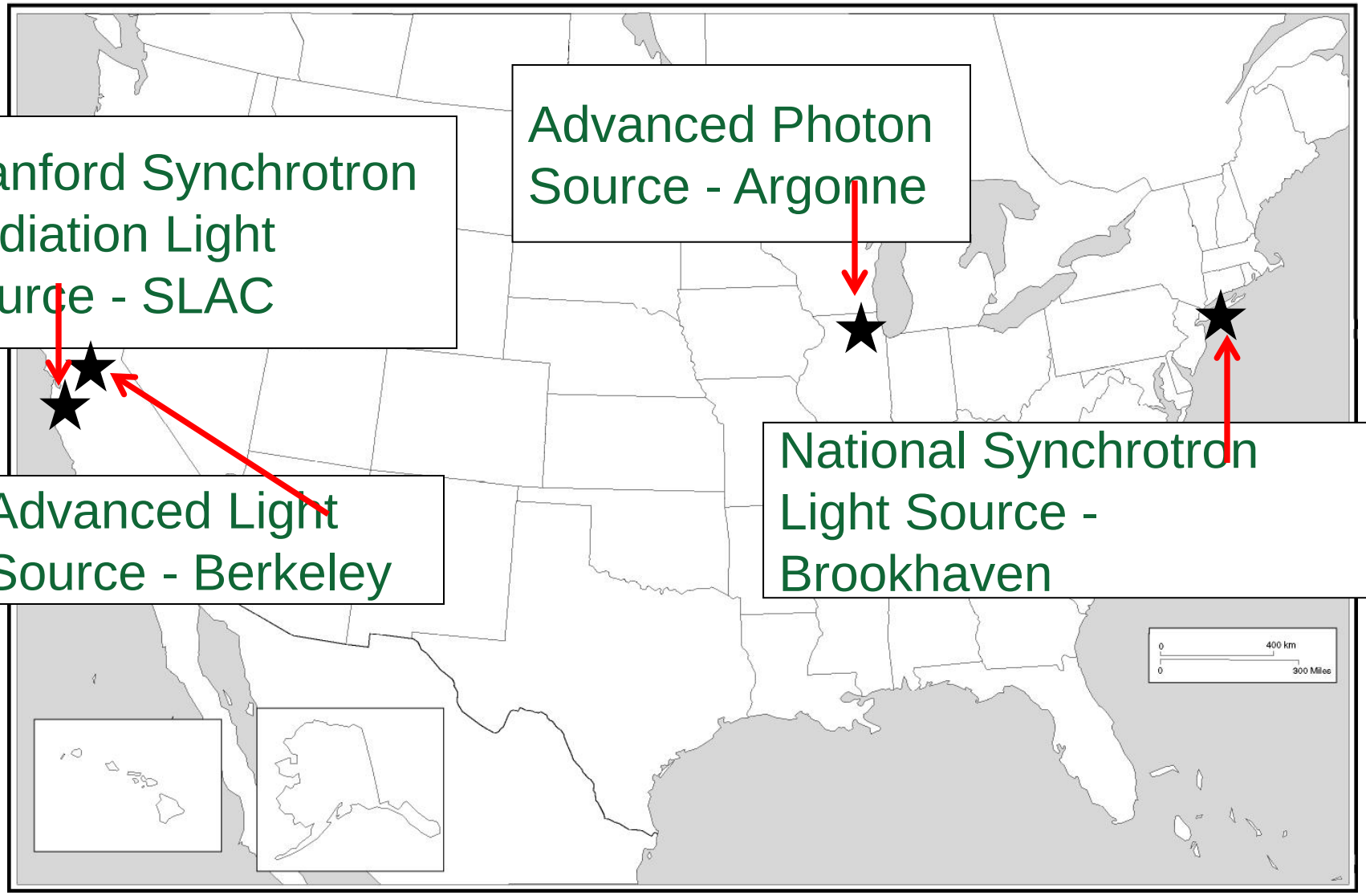
X-Rays are emitted when the e^- traverses the bending magnet or the undulator

Synchrotron Light Sources Evolution By Generation



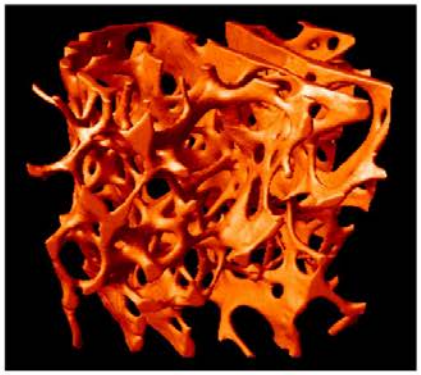
- 1st Gen: parasitic synchrotron radiation source from the dipoles of an HEP collider storage ring (SPEAR, 1975)
- 2nd Gen: dedicated storage ring for synchrotron radiation, dipole radiation & some undulators (NSLS, 1982)
- 3rd Gen: dedicated storage ring optimized for undulator radiation; very high brightness (APS, 1996)

Department of Energy X-Ray Light Sources

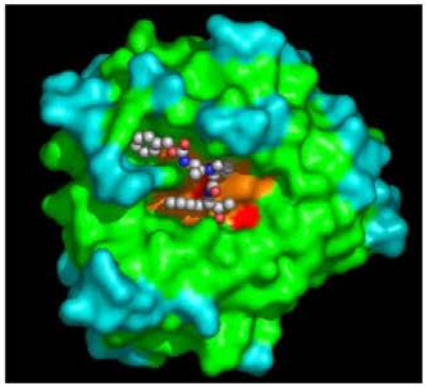


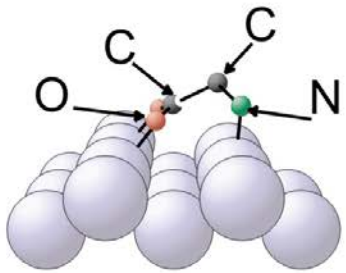
X-Rays Can See the Invisible : Provide Static & Dynamic Info

Nanostructures and their Motions

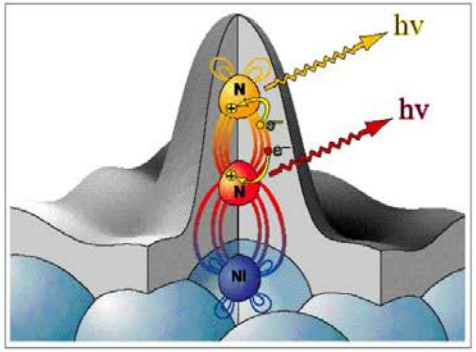


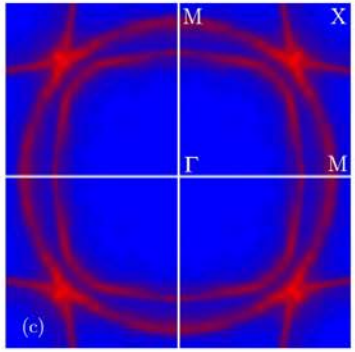
Positions and Motions of Atoms



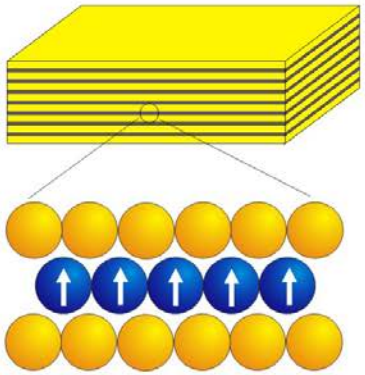


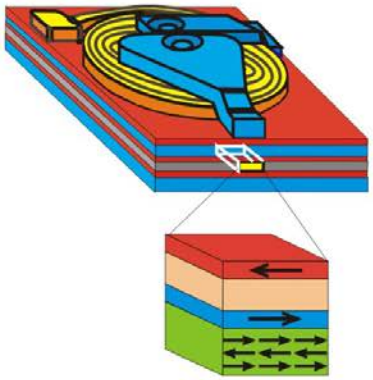
Electron Distributions and their Dynamics





Spin Distributions and their Dynamics





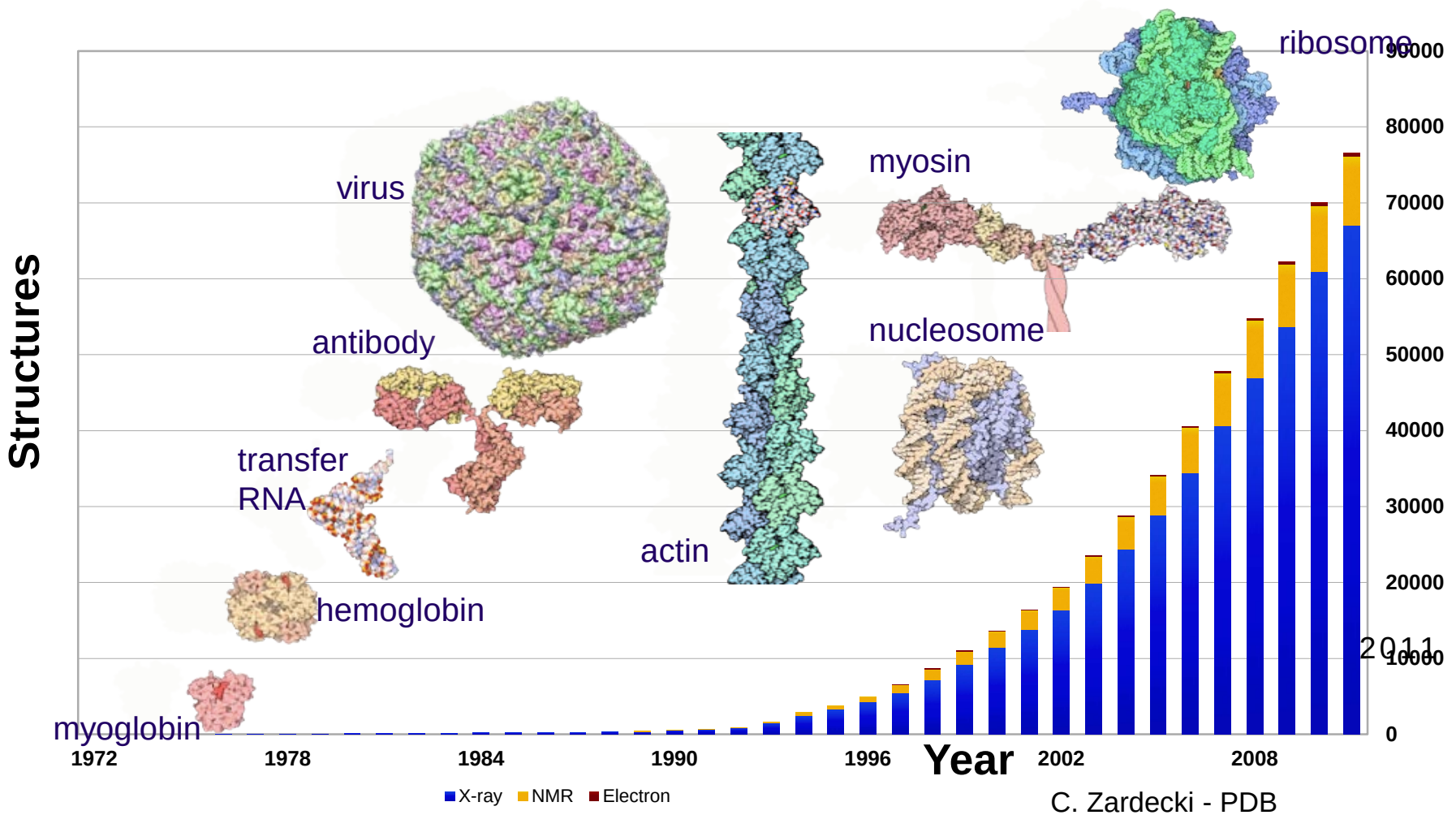
BES Light Sources Serve More Than 10,000 Users Annually

- BES Light Sources have been an SC success story in S&T impact and as key national resource for innovation and competitiveness
- Maintaining U.S. leadership in light sources amidst fierce world-wide competitions is a major challenge for SC and BES

Science Engines: Synchrotron Light Sources Worldwide

Biological Structure: X-Rays are the Key Tool

Cumulative number of structures in the Protain Data Base= 75146 as of Oct 18!

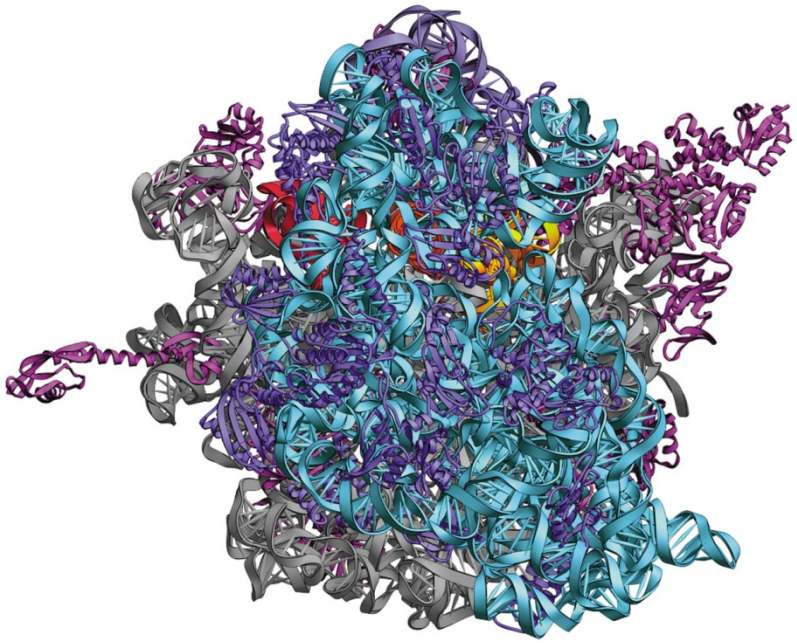


C. Zardecki - PDB

C. Abad-Zapatero - Acta Cryst D68 (2012)

4 Nobel Prizes in 9 Years in Macromolecular Crystallography Using Synchrotron Light Sources

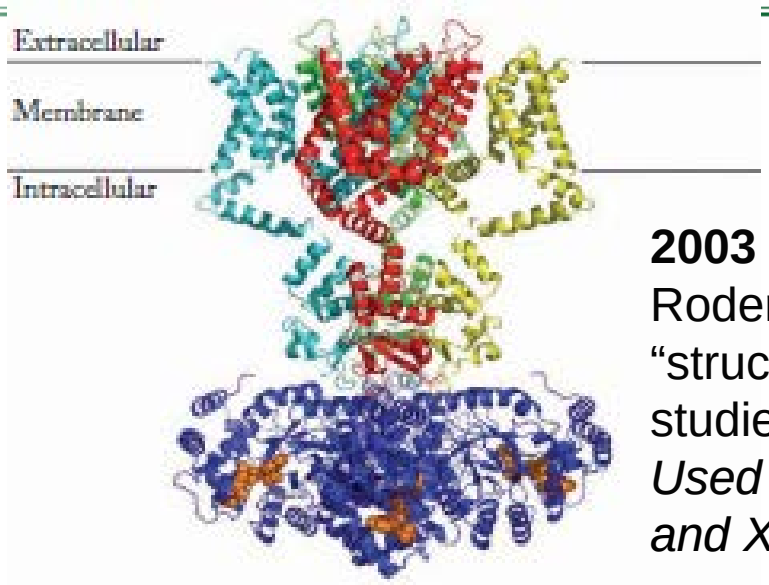
2009 Prize in Chemistry: Venkatraman Ramakrishnan, Thomas Steitz, and Ada Yonath) "for studies of the structure and function of the ribosome." *Used all 4 light sources.*



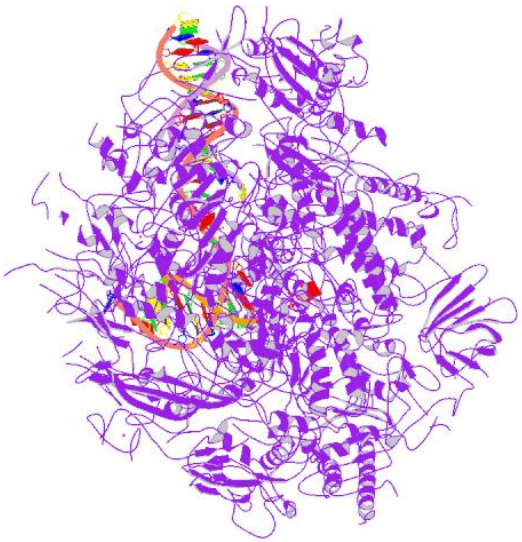
Venkatraman Ramakrishnan

Thomas Steitz

Ada Yonath



2003 Prize in Chemistry: Roderick MacKinnon for "structural and mechanistic studies of ion channels." *Used NSLS beamlines X25 and X29.*



2006 Prize in Chemistry: Roger Kornberg "for his studies of the molecular basis of eukaryotic transcription." *Used SSRL macromolecular crystallography beamlines.*

2012 Nobel Prize in Chemistry

- Awarded to Robert J. Lefkowitz (HHMI and Duke University Medical Center) and Brian K. Kobilka (Stanford University School of Medicine) “for studies of G-protein-coupled receptors.”
- G-protein-coupled receptors (GCPRs) are a class of important chemical receptors that enable cells to interact with and respond to their environment.
- These receptors are responsible for how we see, smell, taste, respond to stress, etc. More than half of all human medications work by signaling to cells via these receptors.

- Dr. Kobilka and co-workers used the high brightness and mirco-focusing capability of the Advanced Photon Source to reveal a high-resolution structure of a receptor in the act of signaling (above). This was cited as the “holy grail” in the quest for understanding the function of GCPRs.

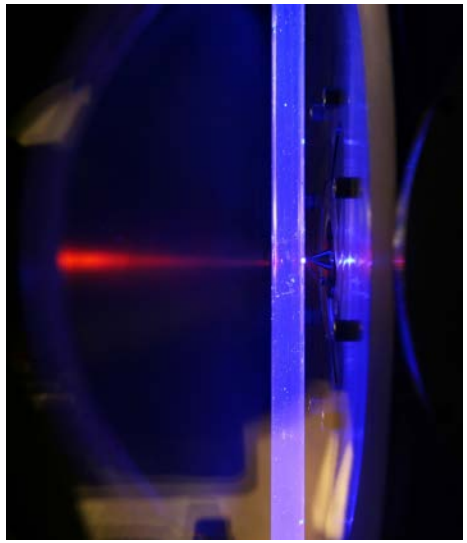
Advanced Photon Source
Argonne National Laboratory

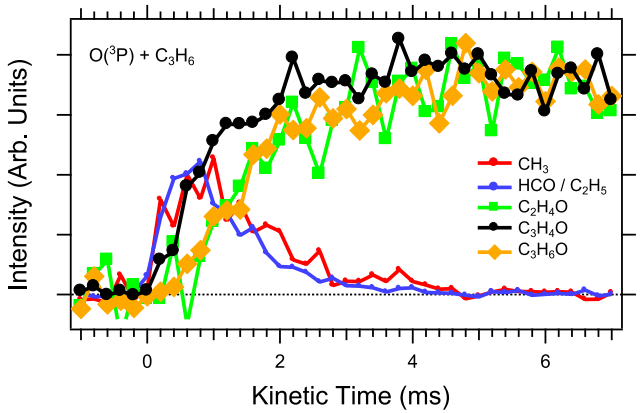
Light Sources Enabling Science: Combustion Chemistry

- Scientists are using the the Advanced Light Source in combination with mass spectrometry to probe combustion reactions in important new ways:
  - The first detection of an elusive chemical intermediate important in combustion and atmospheric chemistry.
  - Unraveling the role of electron spin in determining the pathways for a critical oxidation reaction.

Impact

Benchmark chemistry studies at the ALS provide critical validation for predictive combustion simulation.



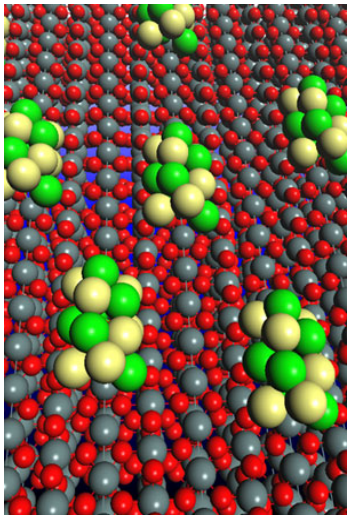


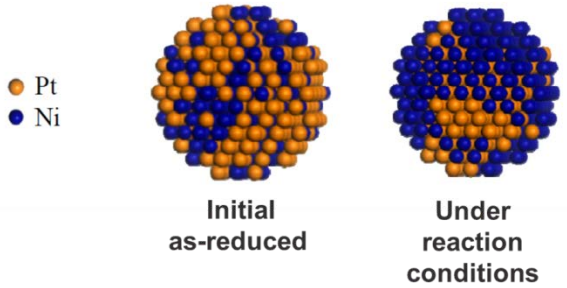
Top: Photo-ionization/mass spectrometry apparatus at the ALS.
Bottom: Kinetic measurements for the O+propene reaction.

Light Sources Enabling Science: Catalysis

BES began the Synchrotron Catalysis Consortium (SCC) in 2006 to promote fundamental catalysis research at NSLS. SCC membership come from academia, national labs, and industry.

- Through dedicated facilities on three NSLS beamlines and assistance/training for potential users, the SCC has increased catalysis science publications by about threefold.
- Recent highlights include:
  - The characterization of a new platinum-rhodium catalyst supported tin oxide that shows promise for ethanol fuel cells.
  - Probing the function of a platinum-nickel catalyst for conversion of biomass to fuels.
  - EXAFS studies of the complex interplay between metal particles an oxide supports in a prototypical catalyst – platinum on alumina.

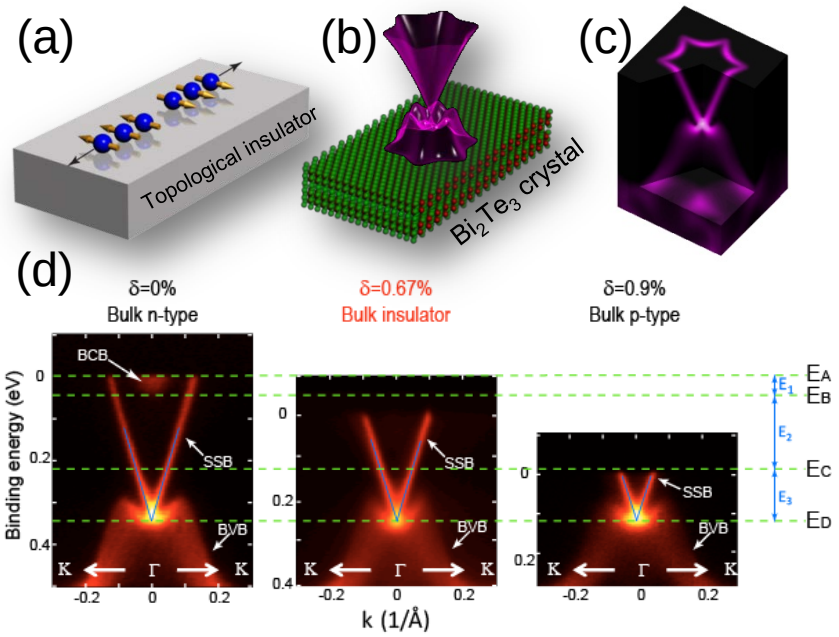




Top: Model of Pt-Rh ethanol fuel cell electrocatalyst on tin oxide surface

Bottom: Changes in Pt-Ni catalysts for biomass conversion during reaction inferred from EXAFS data

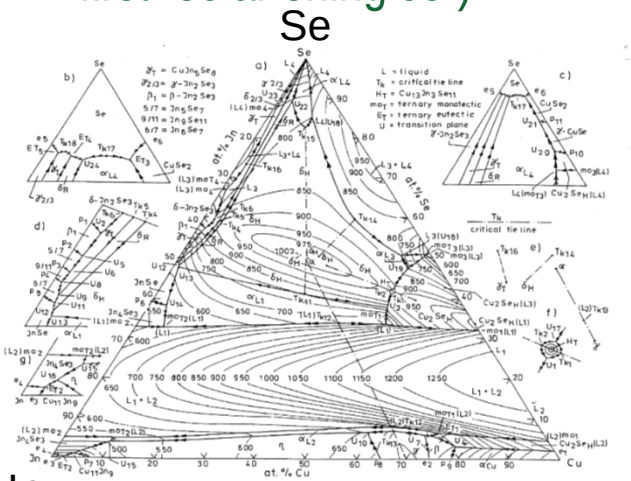
Angle Resolved Photoemission of Surface states on a topological insulator



Large Fortune 500 User Base of BES Scientific Facilities

DOW POWERHOUSE™ Solar Shingles: Reinventing the Roof

- *In situ* x-ray diffraction / differential scanning calorimetry studies researchers from Dow Chemical using the Advanced Photon Source at Argonne National Laboratory investigate process-structure-property relationships in CuInGaSe materials (the active material in the first “solar shingles”).



Investigate the process, structure, and property relationships in CuInGaSe

Opening 2013
Will employ 1200 people by 2015

Solar power that isn’t on the roof, but IS the roof!

Research at APS (2007-2009) → Manufacturing → Marketing

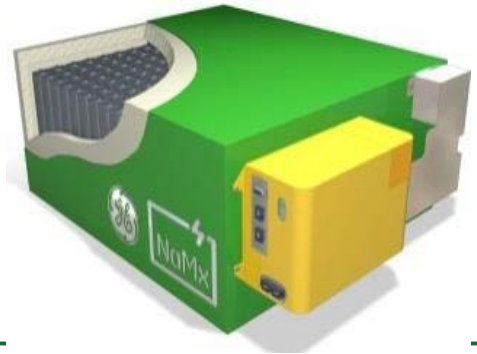
B. Landes, S. Rozeveld, B. Kern, B. Nichols, and J. Gerbi (Dow Chemical Co.)

DOE Light Sources Contribute to American Manufacturing Competitiveness

Revolutionary battery technology leads to a new manufacturing factory in the U.S.

GE researchers used sophisticated scientific capabilities at the NSLS and APS to understand in detail the internal chemistry of an actual commercial battery while charging and discharging in real time. Additional studies of battery cross-sections helped GE engineers to further understand the system to achieve breakthroughs in energy density, charging power, and long cycle life.

Impact:
The new “DurathonTM” sodium metal halide battery.



DOE Light Sources Help Design New Drug Treatment for Alzheimer's Disease

Synchrotron Protein Crystallography provides advanced analysis of protein structures in the drug discovery process

Lilly scientists obtain insights on the function of potential drugs by examining the protein structural information using APS beamline data.

Impact:
A potential drug for Alzheimer's disease, the beta-secretase inhibitor, is currently in Phase I clinical testing.

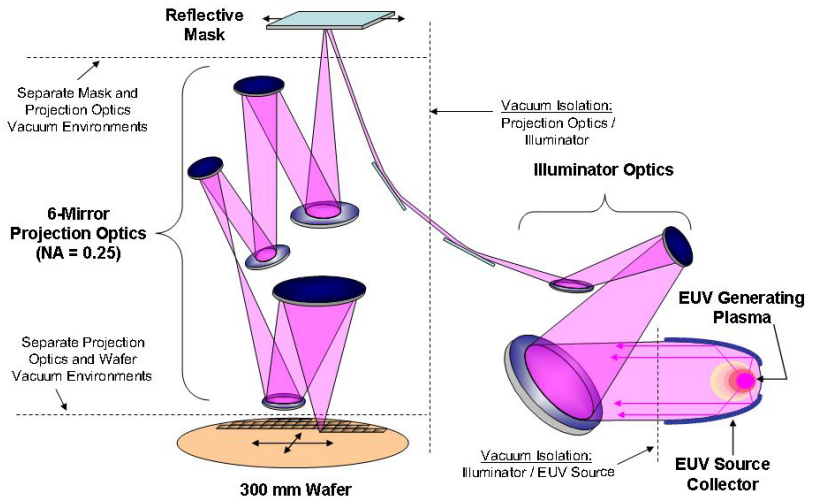
Robotic automation experimental set up for Synchrotron Protein Crystallography

DOE Light Sources Help Accelerate Next Technology Revolution for Semiconductor Industry

Synchrotron EUV Lithography facility provide advanced research on nano-scale manufacturing capability for semiconductor industry

SEMATECH, a consortium of semiconductor companies, uses the EUV Lithography facility at ALS to develop new advanced nano-electronic manufacturing capability toward and beyond as small as 8nm Half-pitch.

Impact:
This work is addressing materials development challenges for nanoscale manufacturing in 2015-2020.

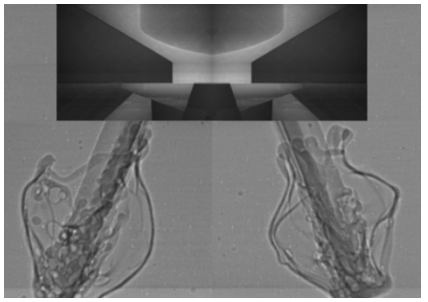


EUV Lithography System

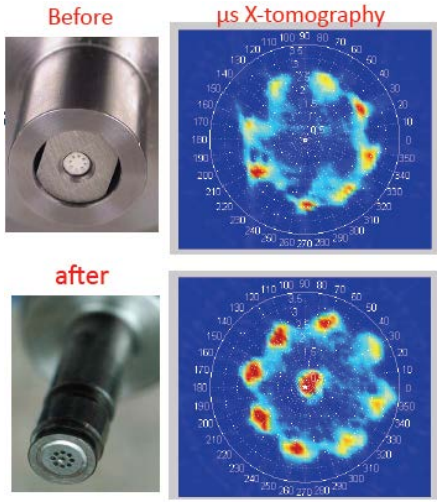
DOE Light Sources Improve Efficiency of Combustion Engines

Visteon®

Synchrotron X-ray Imaging provide crucial information of fuel spray from an injector



Engineers from Visteon Corp. collaborated with APS researchers to develop a new ultrafast synchrotron x-ray full-field phase contrast imaging technique and used it to reveal instantaneous velocity and internal structure of optically dense fuel sprays. This critical knowledge of how fuel is atomized as it is injected led to improvements in fuel injector designs for automobiles and better fuel efficiency.



Impact:
Better and more efficient combustion engines reduce fuel consumptions and air pollution.

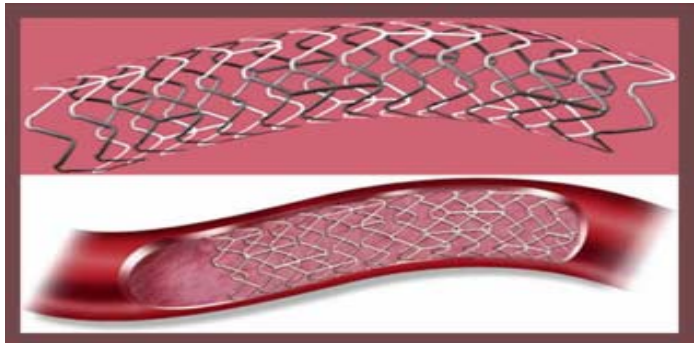
DOE Light Sources Help Improve Life-Saving Stents

Stents, a major component in the fight against heart disease, occasionally deform or fracture. The DOE's X-ray facilities reveal what's going wrong.

Researchers from the materials technology company NDC used the sophisticated scientific capabilities available at SSRL and ALS to understand the effects of microstructure on the stability and lifetime of superelastic stent scaffolds.

A comparison of the microstructure of two nitinol stents identical in all ways except processing conditions, shows why they exhibit dramatically different mechanical response.

Impact:
This work resulted in new design guidelines for safer and longer lasting superelastic vascular stents.



http://www.xebradigital.com/img/stent_image.jpg

DOE Light Sources Spur New Small Companies

The technologies and know-how developed at DOE light sources serve as the seeds for new companies located across the U.S.

Research and development activities at DOE light sources create a great variety of opportunities for commercial ventures, including the foundation of new start-up companies.

Such spin-off companies include Xradia (imaging products), InSync (custom high-tech mirrors), ADSC (CCD detectors) and XIA (detector electronics).

Impact: DOE light sources give rise to small businesses, create jobs.

DOE Light Sources Solve Night Vision Limitation

INTEVAC

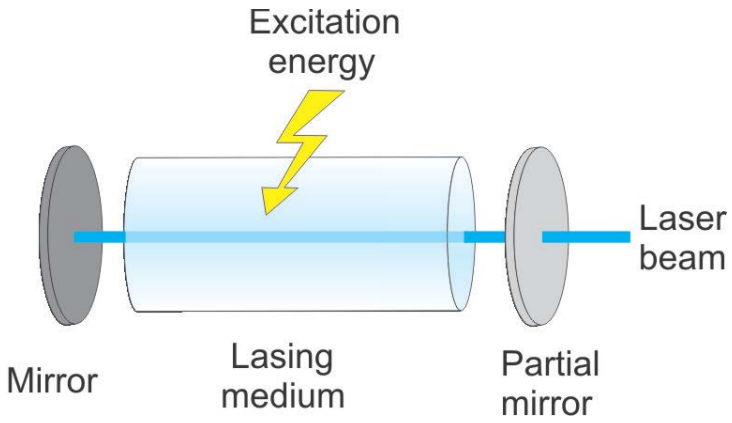
DOE light source makes manufacturing breakthrough for advanced night vision tubes.

The next-generation night vision systems—important for both military and civilian surveillance applications—were plagued by a short shelf life in temperatures above 70°F. Through studies at SSRL, researchers developed new surface cleaning processes for the sensors' advanced semiconductors that completely eliminated the shelf life problem. In addition, the sensitivity was increased significantly.

Impact:
This breakthrough insures that these sensors meet military specifications and can be incorporated into systems under development by both the Army and the Air Force.

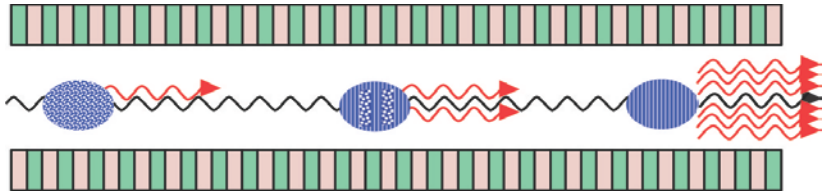
What is an X-ray Free Electron Laser (FEL)?

Optical laser



- **bound electrons in atoms**
  - transitions between discrete states
- **amplification through stimulated emission**
- **fixed photon energy around 1 eV**
- **compact size**

X-ray Free Electron Laser



- **free electrons in bunch**
  - radiation in periodic magnetic field
- **amplification through**
  - **electron bunch orders in its own radiation (SASE)**
  - **electron bunch orders in imposed radiation (seeding)**
- **tunable photon energy > 1000 eV**
- **very large size**

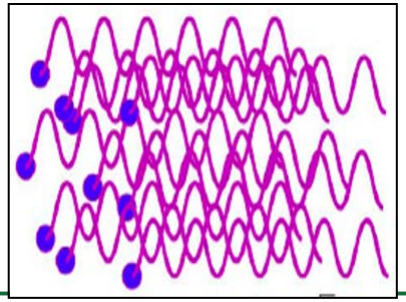
X-FELs vs Storage Ring Sources & Optical Lasers

X-FELS vs. Storage Ring Sources:

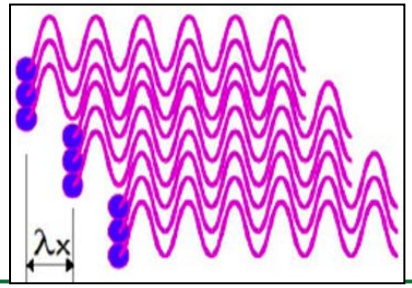
shorter, higher intensity pulses
photons are coherent

- single pulse experiments possible
- pulses faster than atomic motion
- pulses faster than spin processes & some electronic processes
- many identical x-rays simult. in sample

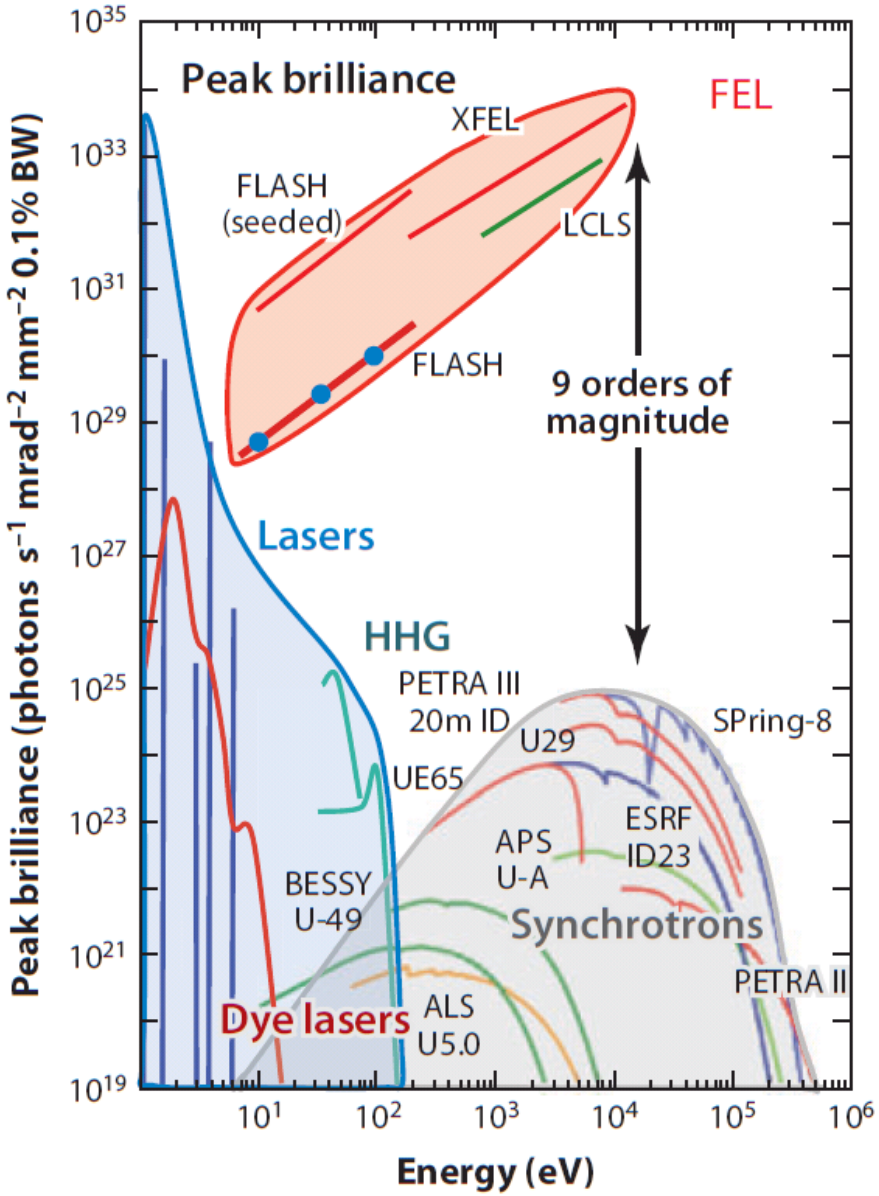
Storage Rings
Spontaneous Radiation



X-FELs:
Coherent Radiation

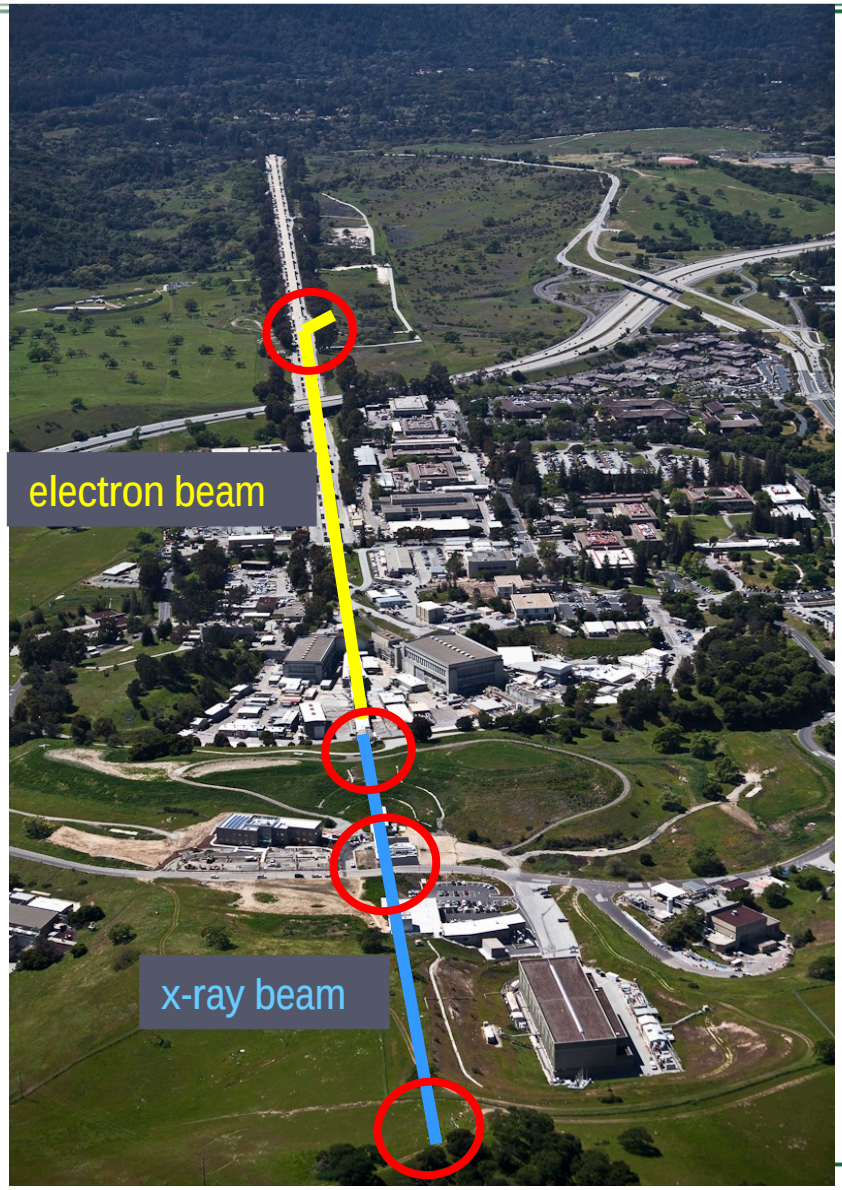


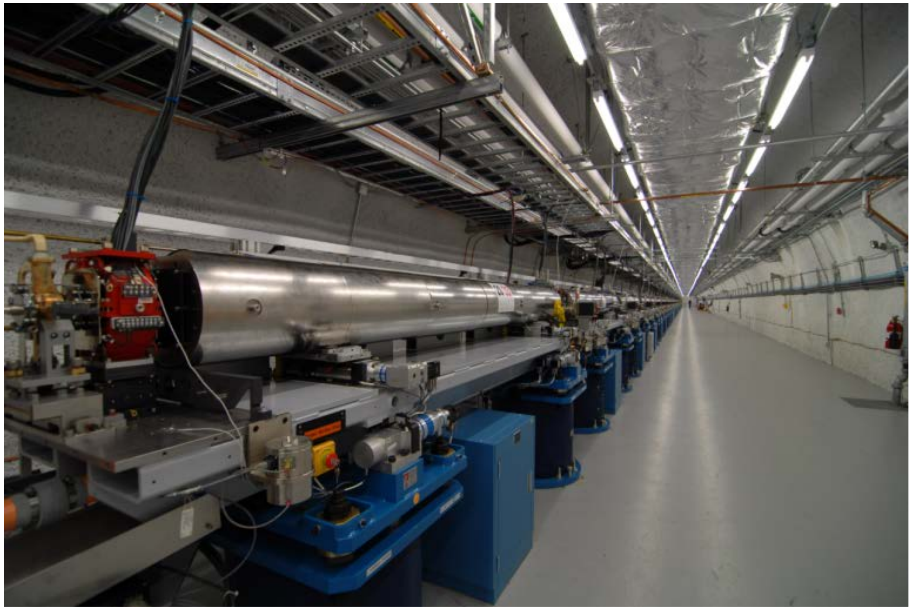
Overview of "Light Sources"



J. Ullrich, A. Rudenko, R. Moshammer
Ann. Rev. Phys. Chem. **63**, 635 (2012)

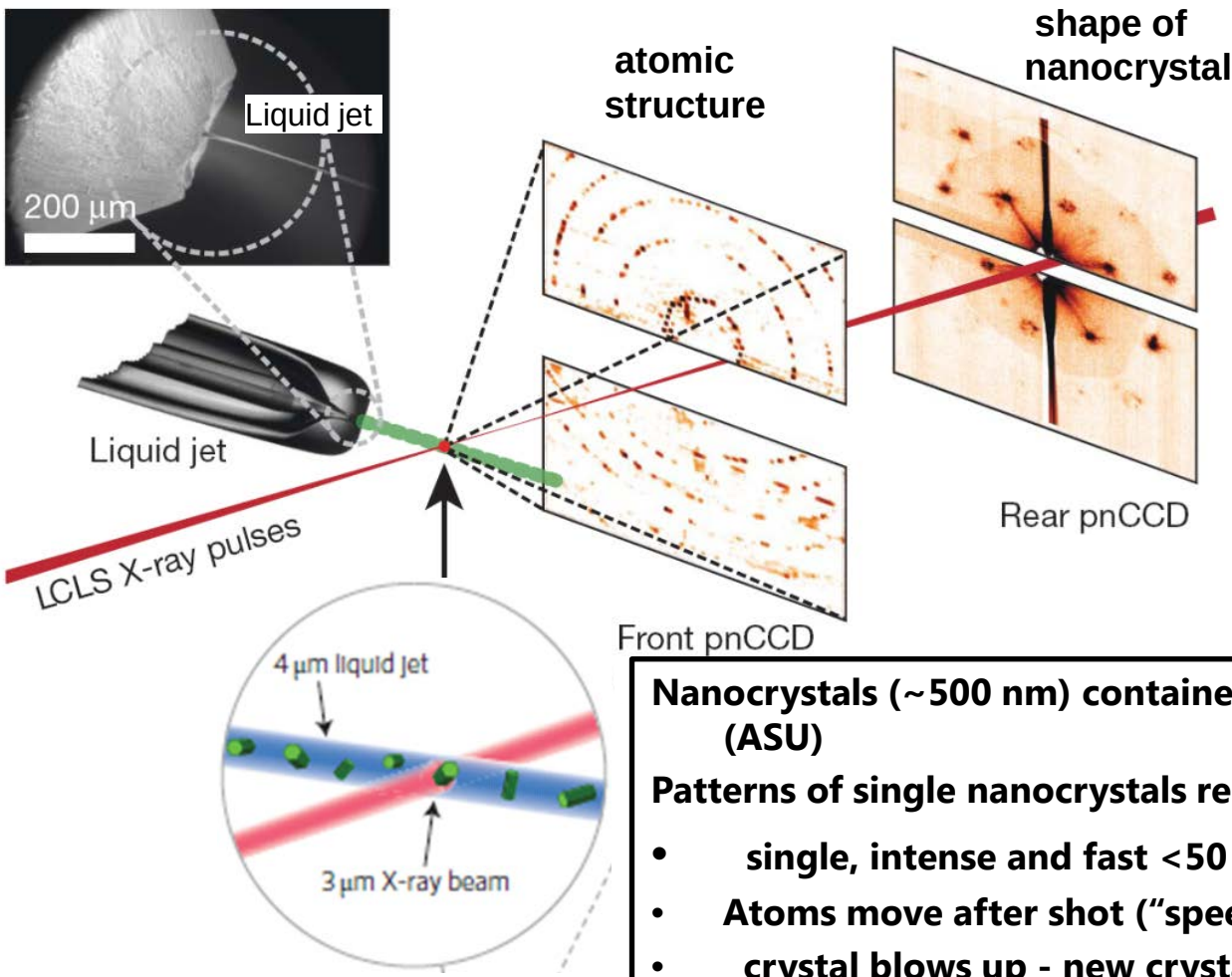
Linac Coherent Light Source (LCLS)
The World's First X-ray Free Electron Laser





Femtosecond Protein Nano-Crystallography

Beating the Speed of Sound with the Speed of Light



Nanocrystals (~500 nm) contained in water jet (ASU)

Patterns of single nanocrystals recorded in

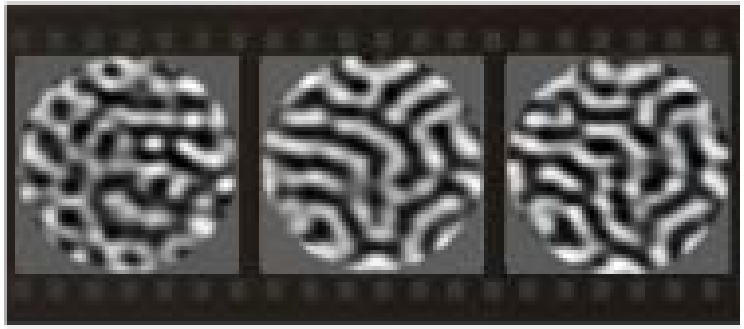
- **single, intense and fast <50 fs x-ray shots**
- **Atoms move after shot ("speed of sound")**
- **crystal blows up - new crystal for new shot**

Complete structure from ~1 million shots

Ultra-fast Single-shot Imaging for Next Generation Magnetic Storage

The LCLS has demonstrated a new approach to image – at ultrafast speeds – how variations in the electronic structure of materials impact magnetic properties

Researchers have taken the fastest ever snapshots of nanoscale magnetic structures with single femtosecond pulses of X-rays thus paving the way for making ultrafast movies of information processing and understanding future magnetic data storage devices.



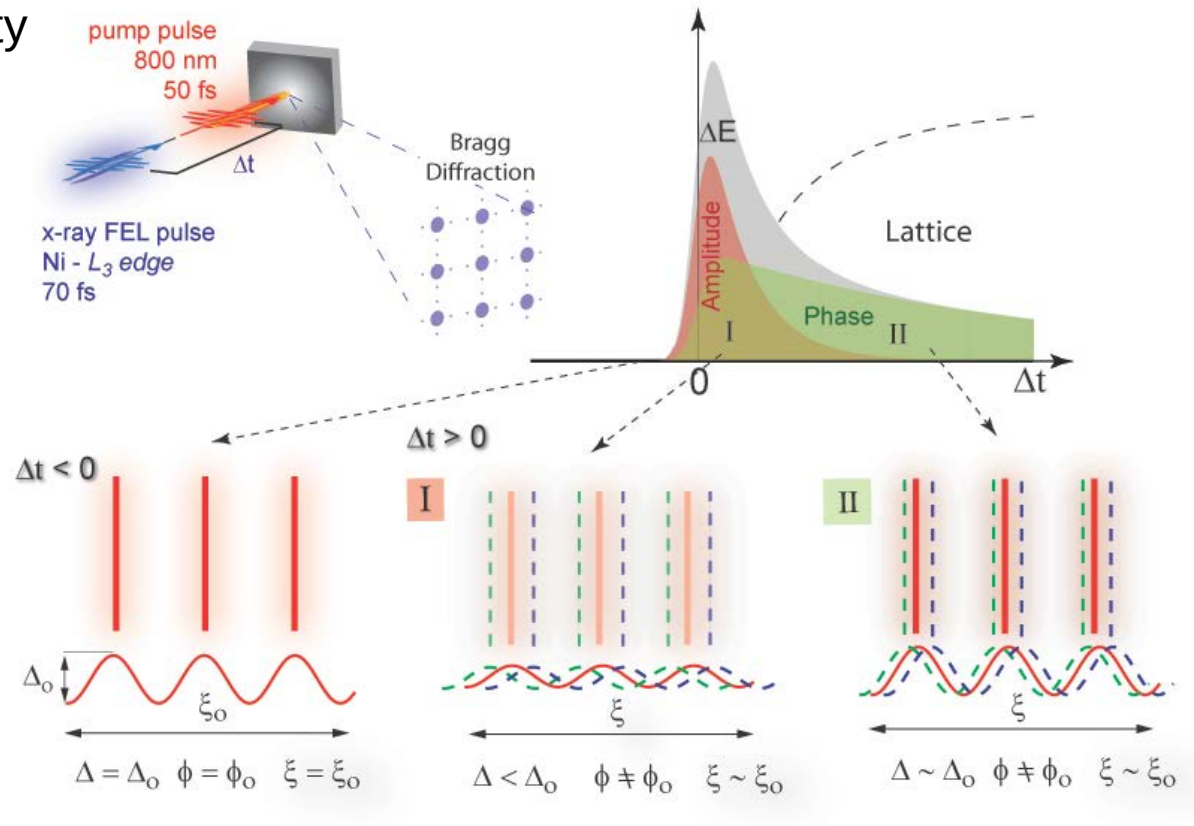
Reconstructed single shot holograms

Impact: The information learned for ultrafast characterization will provide the understanding required to design next generation materials for technological applications such as magnetic recording devices and spintronics devices.

X-ray Free Electron Laser (FEL) Sheds New Light on Superconducting Behavior

Time resolved measurements at the LCLS reveal the exquisite physics underlying superconductivity – the ability to conduct electricity with no transmission losses.

For the first time, research was able to disentangle two key features in the atomic scale ordering phenomena believed to control superconductivity.



W. S. Lee *et al.* Nature Communications Vol 3, Article number: 838

Concluding Remarks

- 80 years of advances in accelerator science used to generate intense beams of x-rays
- Electron storage rings are the work horses, while free electron lasers command the realm of extreme peak power experiments
- DOE SC light sources enable breakthrough science in the fields of biology, chemistry, geo, material & physical science
- US industry is driving innovative product development & job creation by using the light sources
- DOE SC's strategy is to ensure that it provides the best x-ray sources to the SC scientific user community