The Jefferson Lab Amplifier (JLAMP) Project

Gwyn P. Williams

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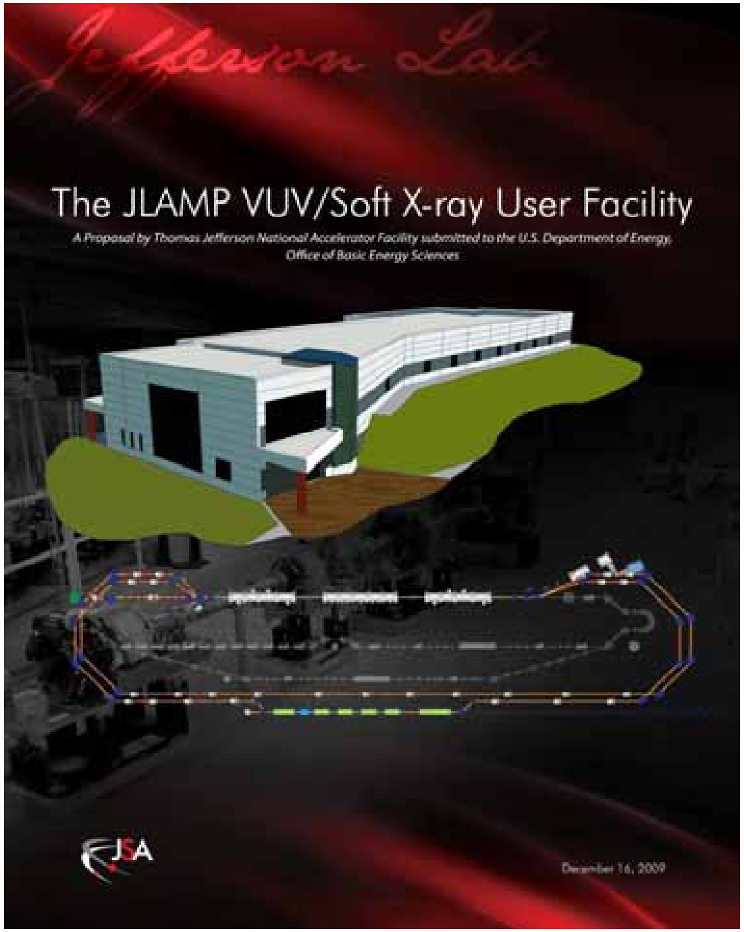
& the JLab Team

Jefferson Lab

12000 Jefferson Avenue

Newport News, Virginia 23606

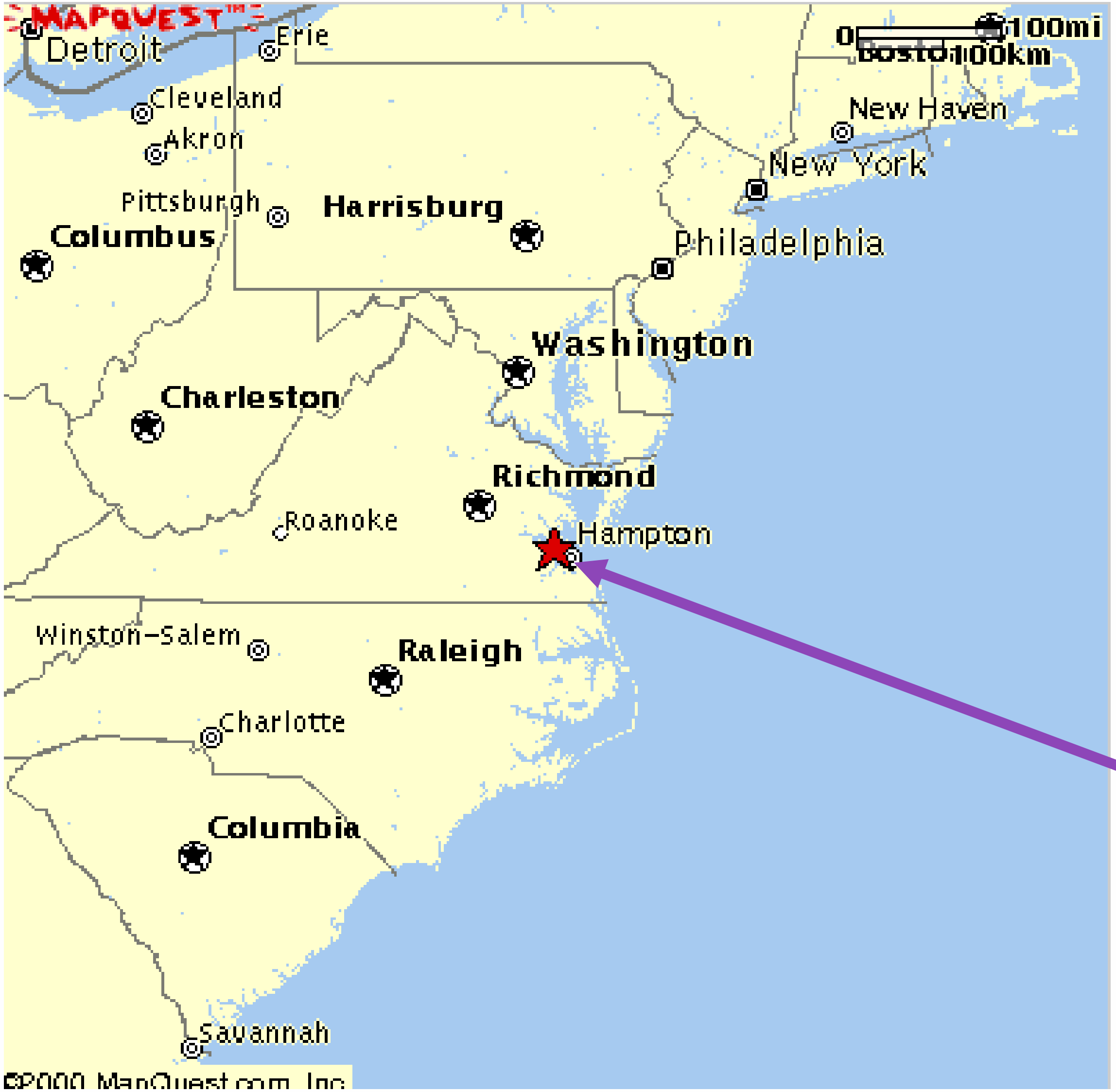


PNNL, March 30, 2010

Talk Outline

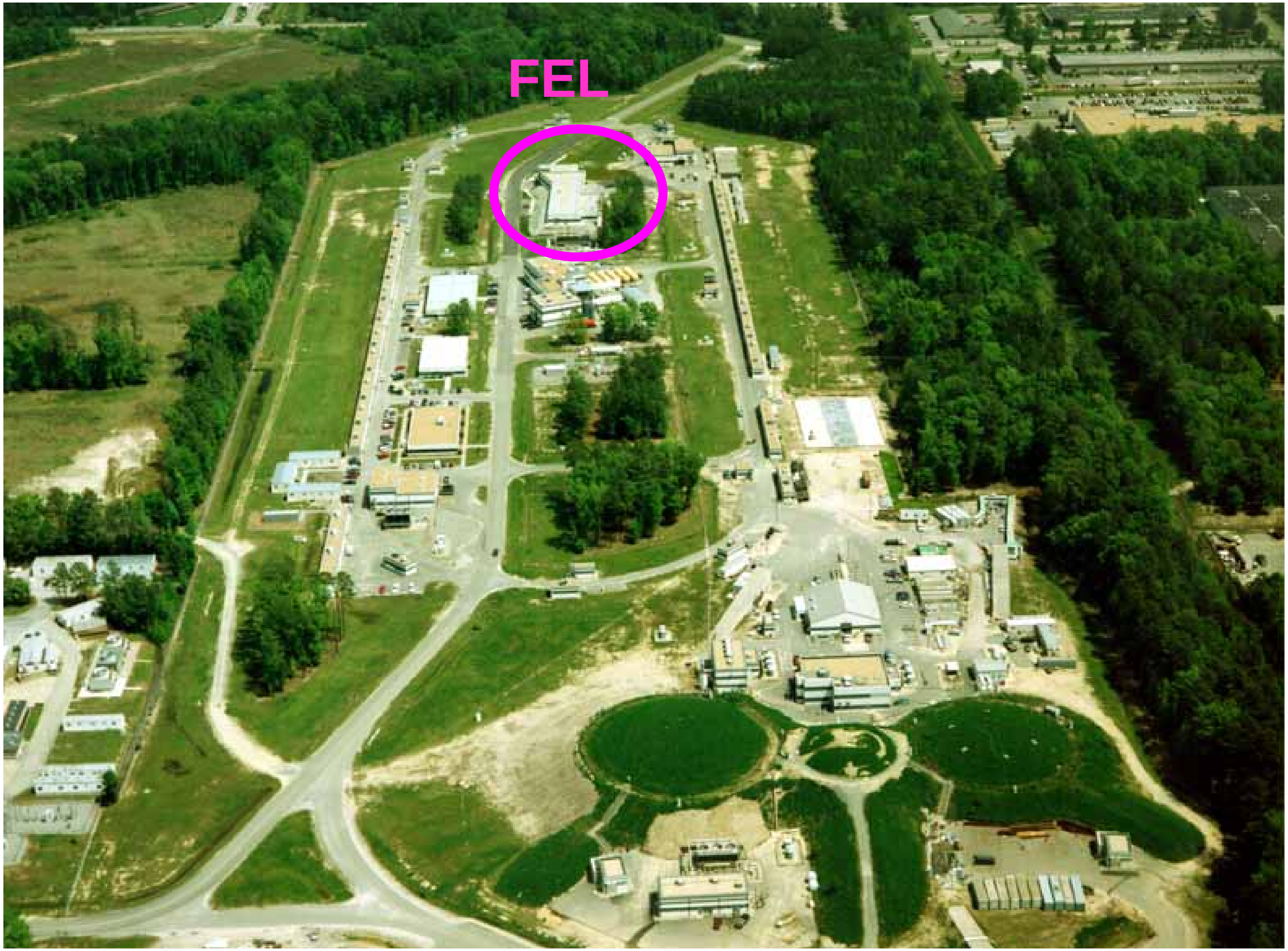
- Background/motivation for 4th generation light sources
- Context of 4th generation light sources
- Science motivating these sources
- Jefferson Lab's new proposal, called JLAMP

Jefferson Lab - where are we?

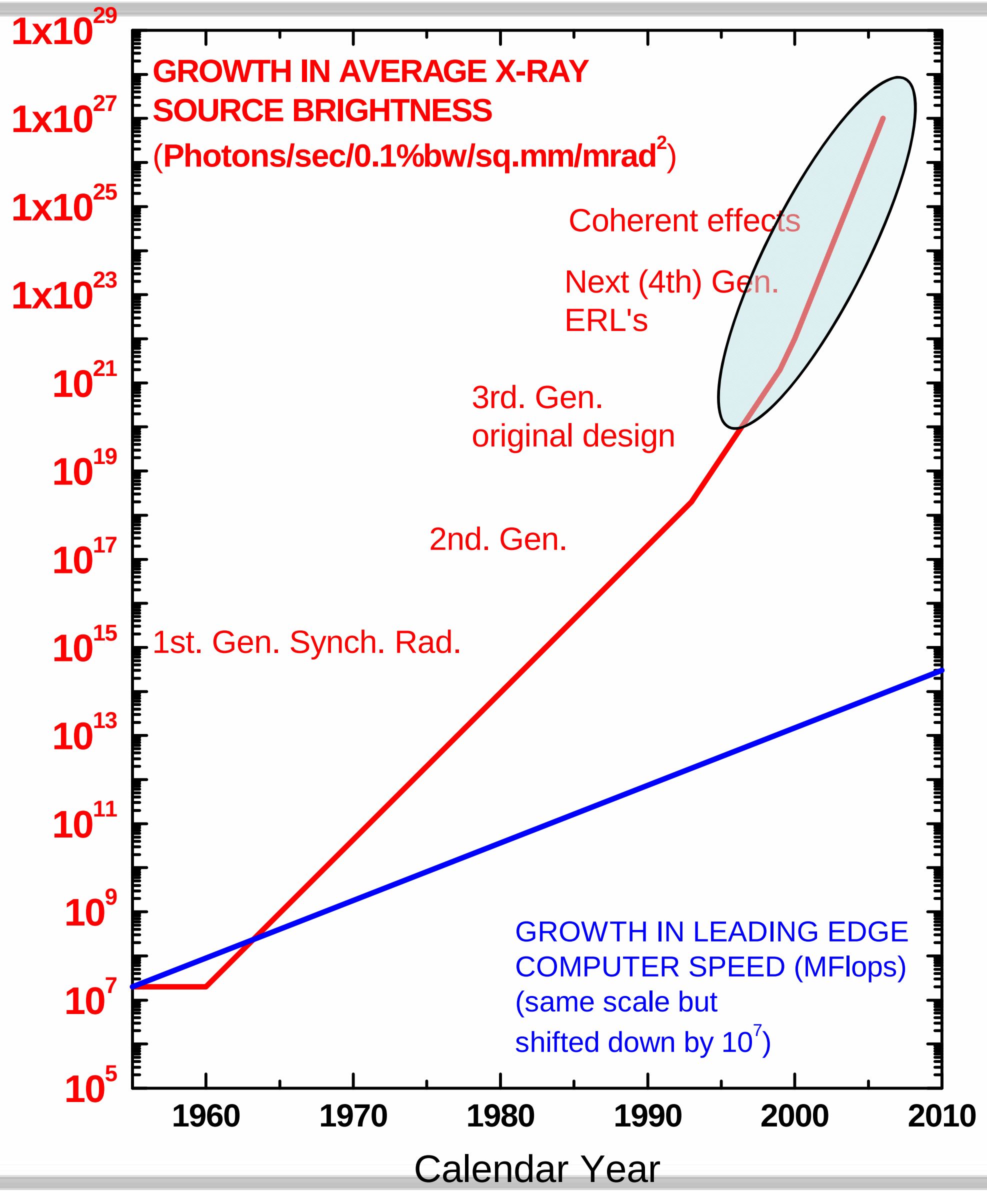


Jefferson Lab

Jefferson Lab, Newport News, VA



Dramatic increase in light source brightness…



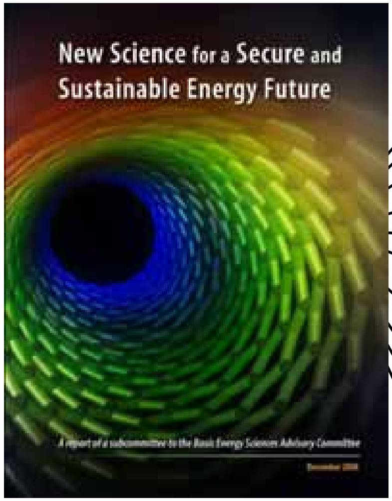
DOE's Office of Science

<u>Three themes</u> describe the work supported by the Office of Science:

- **Science for discovery**
  - Unraveling Nature's deepest mysteries—from the study of subatomic particles; to atoms and molecules that make up the materials of our everyday world; to DNA, proteins, cells, and entire natural ecosystems
- **Science for national need**
  - Advancing a clean energy agenda through basic research on energy production, storage, transmission, and use
  - Advancing our understanding of the Earth's climate through basic research in atmospheric and environmental sciences and in climate modeling
  - Supporting DOE's missions in national security
- **National user facilities, the 21st century tools for science, engineering, and technology**
  - Providing the Nation's researchers with the most advanced tools of modern science including accelerators, colliders, supercomputers, light sources and neutron sources, and facilities for studying the nanoworld, the environment, and the atmosphere

The 10 DOE "Basic Research Needs" Workshops

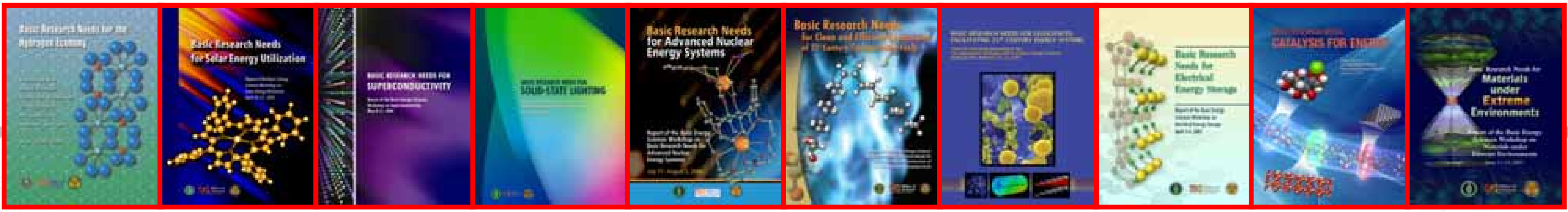
10 workshops; 5 years; more than 1,500 participants from academia, industry, and DOE labs



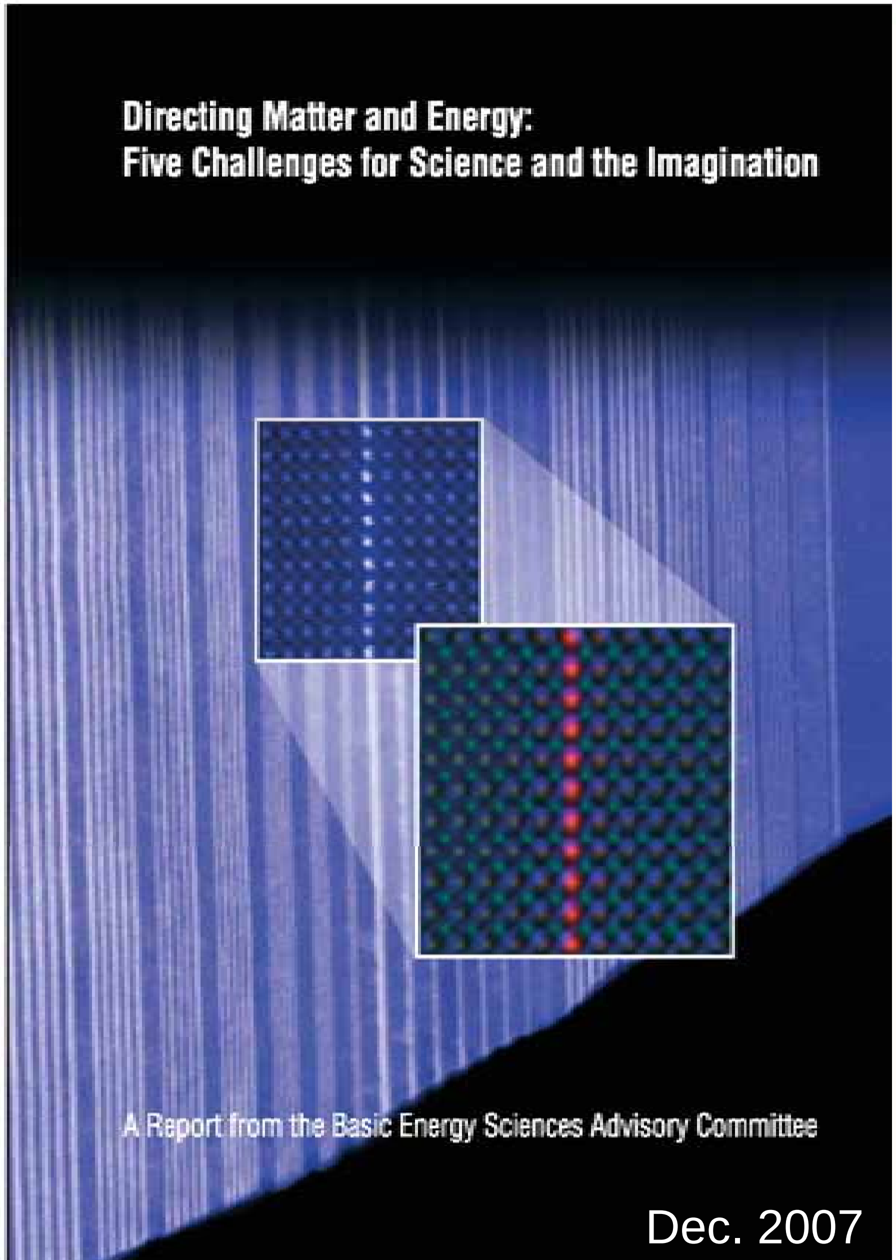
- Basic Research Needs for the Hydrogen Economy
- Basic Research Needs for Solar Energy Utilization
- Basic Research Needs for Superconductivity
- Basic Research Needs for Solid State Lighting
- Basic Research Needs for Advanced Nuclear Energy Systems
- Basic Research Needs for the Clean and Efficient Combustion of 21st Century Transportation Fuels
- Basic Research Needs for Geosciences: Facilitating 21st Century Energy Systems
- Basic Research Needs for Electrical Energy Storage
- Basic Research Needs for Catalysis for Energy Applications
- Basic Research Needs for Materials under Extreme Environments

www.science.doe.gov/bes/reports/list.html

courtesy Pat Dehmer



“Directing Matter and Energy: Five Challenges for Science and the Imagination"



Dec. 2007

FOUR GENERATIONS OF LIGHT SOURCES

The First Three Generations. Electron synchrotrons have evolved through three generations to provide highly optimized x-ray sources for diffraction, imaging, and spectroscopy. They are based on electron storage rings around which electrons travel in "bunches" of tens to a few hundred picoseconds in duration. When forced to follow a curved path through bending magnets or directed through a linear array of periodic magnets (known as insertion devices, which come in two flavors—undulators and wigglers), the electrons emit light pulses of duration equal to that of the electron bunches. The Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory, the Advanced Photon Source (APS) at Argonne National Laboratory, and the Stanford Synchrotron Radiation Laboratory (SSRL) are all third generation sources. The National Synchrotron Light Source II (NSLS-II) at Brookhaven National Laboratory will be a green-field, third-generation replacement for the original NSLS, with enhanced capabilities, particularly brightness, that push storage-ring technology to its limit.

Fourth-Generation. Interrogating atoms, molecules and materials with coherent light pulses on the timescale of the electron motion is a critical first step toward control at the quantum level (see Chapter 2). For such experiments, a light source is needed with all of the properties of a laser beam but with photon energies tunable from VUV into the x-ray region and pulse durations from picoseconds to attoseconds. A light source with the following properties would create great opportunities:

- Even higher flux, brightness, peak power (power per pulse), average power, and stability than available with the third-generation synchrotron radiation sources (Figure 1).
- Much shorter pulse widths and hence temporal resolution.
- Temporal and spatial coherence.

Providing these properties requires redesigning the familiar synchrotron storage ring to capture some of the emittance advantages of a linear accelerator (linac). Energy-recovery linacs (ERL) and free-electron lasers (FEL) are first attempts in this direction, and more novel designs that combine laser and accelerator technology appear likely in the future. No single machine will optimize all of the improvements listed above. For example, high-peak-power machines may not provide the best stability and average power.

In the United States, the Linac Coherent Light Source (LCLS) at the Stanford Linear Accelerator Center is being built as an x-ray laser at a wavelength of 1.5 Å. The Thomas Jefferson National Laboratory operates an ERL that drives an infrared FEL at a repetition rate up to tens of megahertz. Efforts to extend performance of FELs and ERLs are being actively pursued around the world.

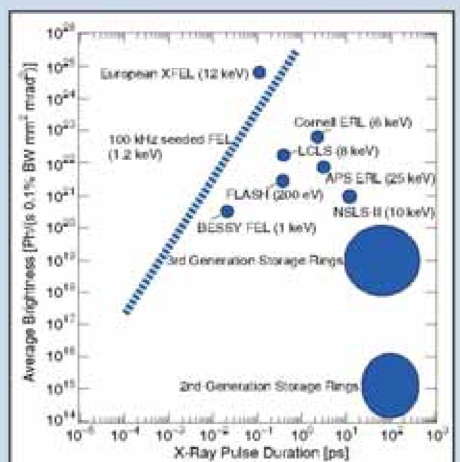


FIGURE 1. Average brightness as a function of pulse duration for representative storage-ring, ERL, and FEL sources in the VUV to x-ray range. For identified proposals, values are shown for design brightness at the photon energies indicated in parentheses, based on available data.

BES Grand Challenges

Directing Matter and Energy; 5 Challenges for Science & the Imagination

1. **How do we control materials processes at the level of the electrons?**
   Pump-probe time dependent dynamics, ARPES

2. **How do we design and perfect atom- and energy-efficient synthesis of new forms of matter with tailored properties?**
   PLD, photo-chemistry, XRS, ARPES

3. **How do remarkable properties of matter emerge from the complex correlations of atomic and electronic constituents and how can we control these properties?**
   Pump-probe time dependent dynamics, XRS, ARPES

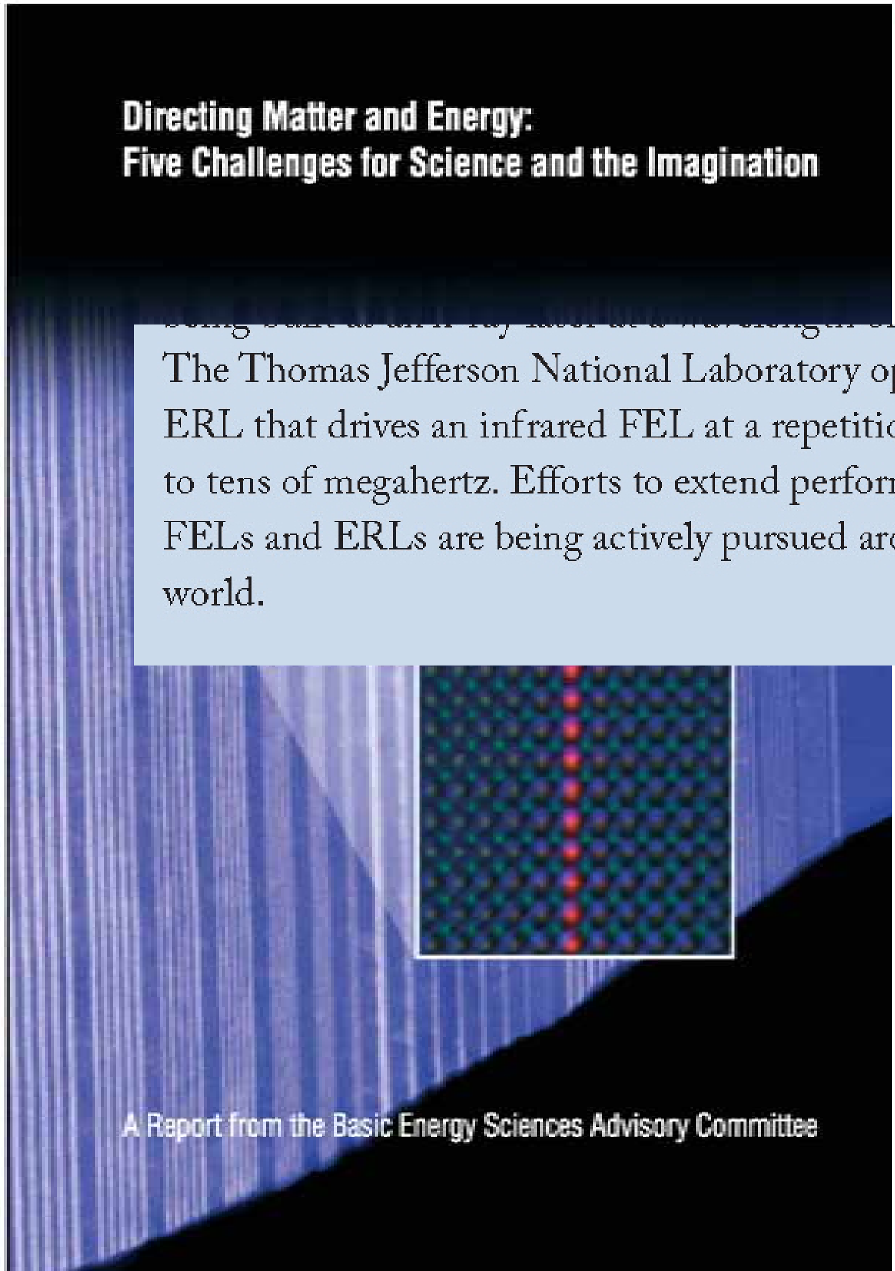
4. **How can we master energy and information on the nanoscale to create new technologies with capabilities rivaling those of living things?**
   Pump-probe time dependent dynamics, XRS, ARPES

5. **How do we characterize and control matter away -- especially very far away -- from equilibrium?**
   Non-linear dynamics, ultra-bright sources

Report - Graham Fleming and Mark Ratner (Chairs).

Ultrafast, ultrabright, tunable THz/IR/UV/X-Ray light from next generation light sources

The Tools determine the science possible



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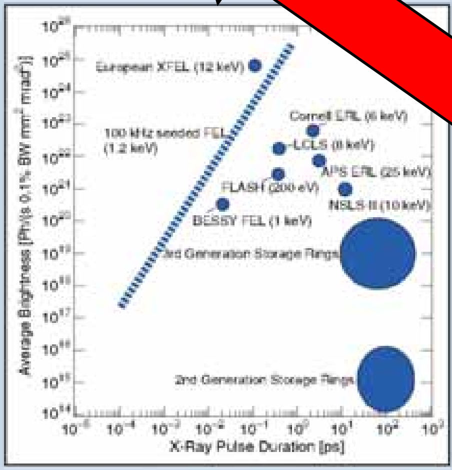

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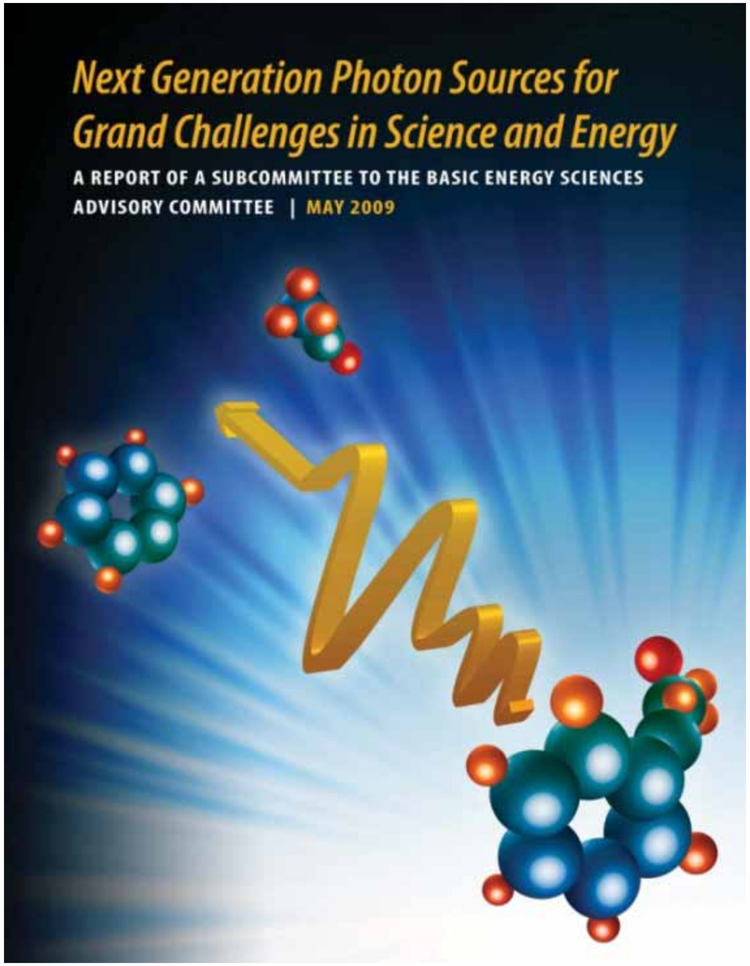
The reports make a compelling case for use of high power and brightness for fundamental studies of equilibrium and non-equilibrium properties of novel materials.

And culminated in a report outlining the photon sources needed.



BES Scientific User Facilities

Light sources

Stanford Synchrotron Radiation Laboratory (SLAC)
National Synchrotron Light Source (BNL)
National Synchrotron Light Source II (BNL)
(start construction FY 2009)
Advanced Light Source (LBNL)
Advanced Photon Source (ANL)
Linac Coherent Light Source (SLAC) (in commissioning FY 2010)

Neutron sources

Manuel Lujan, Jr. Neutron Scattering Center (LANL)
High Flux Isotope Reactor (ORNL)
Spallation Neutron Source (ORNL)

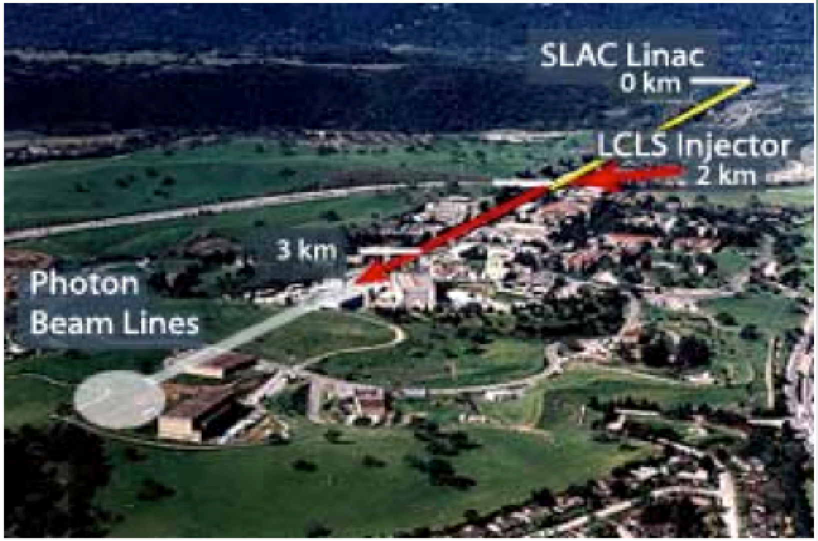
Electron beam sources

Electron Microscopy Center for Materials Research (ANL)
National Center for Electron Microscopy (LBNL)
Shared Research Equipment Program (ORNL)

Nanoscale Science Research Centers

Center for Nanophase Materials Sciences (ORNL)
Molecular Foundry (LBNL)
Center for Integrated Nanotechnologies (SNL/A & LANL)
Center for Functional Nanomaterials (BNL)
Center for Nanoscale Materials (ANL)

Artist's rendition of National Synchrotron Light Source-II



Linac Coherent Light Source

Accelerator Physics of the Next Generation Light Sources

Accelerator Physics of the
Next Generation
Light Sources
Report

February 2010

Workshop Co-chairs:

- John Corlett (LBNL)
- Bill Barletta (MIT)

Date: September 15 -17, 2009

NEWS NATURE|Vol 459|7 May 2009

Leading lights

China is not the only country brightening up its X-ray sources. Two other new light-source facilities, the Linac Coherent Light Source (LCLS) in Stanford, California, and the Positron-Electron Tandem Ring Accelerator (PETRA) III, in Hamburg, Germany, have opened in the past month. And more than a dozen are under way elsewhere (see map).

This 'fourth generation' of new facilities improves on older synchrotrons by making photon beams that are many orders of magnitude brighter, and delivering

Next Generation Light Sources USA Programs

1. Jefferson Lab, UV/IR/THz ERL, operational
2. LCLS, Stanford, USA, hard x-ray, DOE-BES under construction
3. Cornell University, hard x-ray ERL, proposal to NSF, initial funding
4. Florida State University, IR/THz ERL, proposal to NSF, initial funding
5. WiFEL, Stoughton, Wisconsin, soft x-ray, proposal to NSF
6. Next Generation Light Source, Berkeley, soft x-ray, white paper phase
7. Advanced Photon Source, Argonne, hard x-ray ERL, ideas phase
8. LSU, THz – soft x-ray, white paper preparation to State and DOE
9. Light Source of the Future, DOE-BES, TBD
10. Also of note: PEP-X, Stanford, the "ultimate storage ring", preliminary ideas

What are (4th) Next Generation Light Sources?

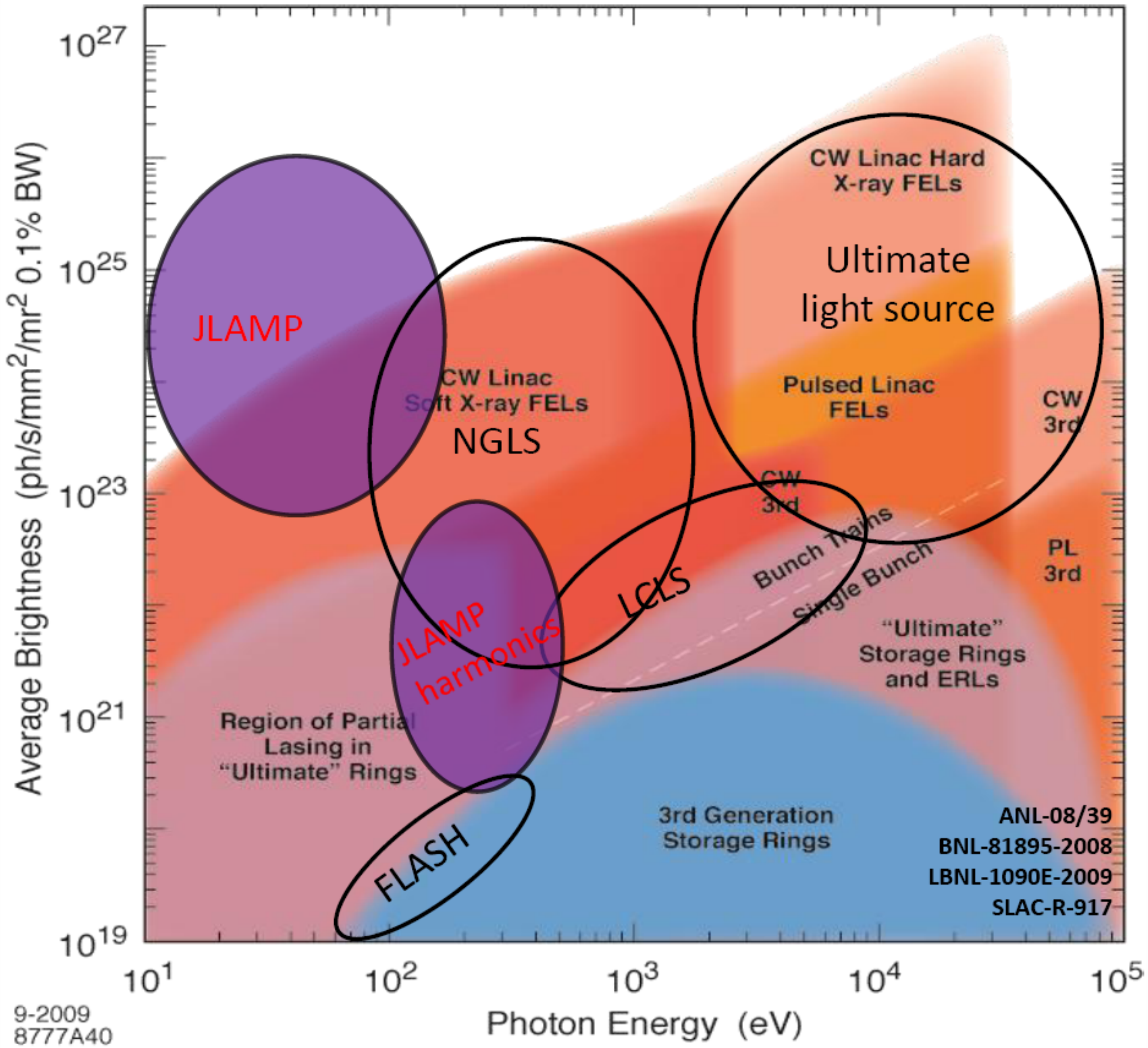
1. First of new generation – they do not displace 3rd generation NSLS-2 is very important
2. Superconducting radio-frequency linac based.
3. Use multiparticle coherence (or "gain").

- Big discussion over whether both 2 & 3 of above, and if 3, then how - SASE, oscillators, seeded amplifiers?
- Big discussion over peak & average current (do we need ERL for example?), and power per pulse.
- Use science to define machine parameters.
- JLab and LCLS are the first of the 4th generation light sources operating in the USA.

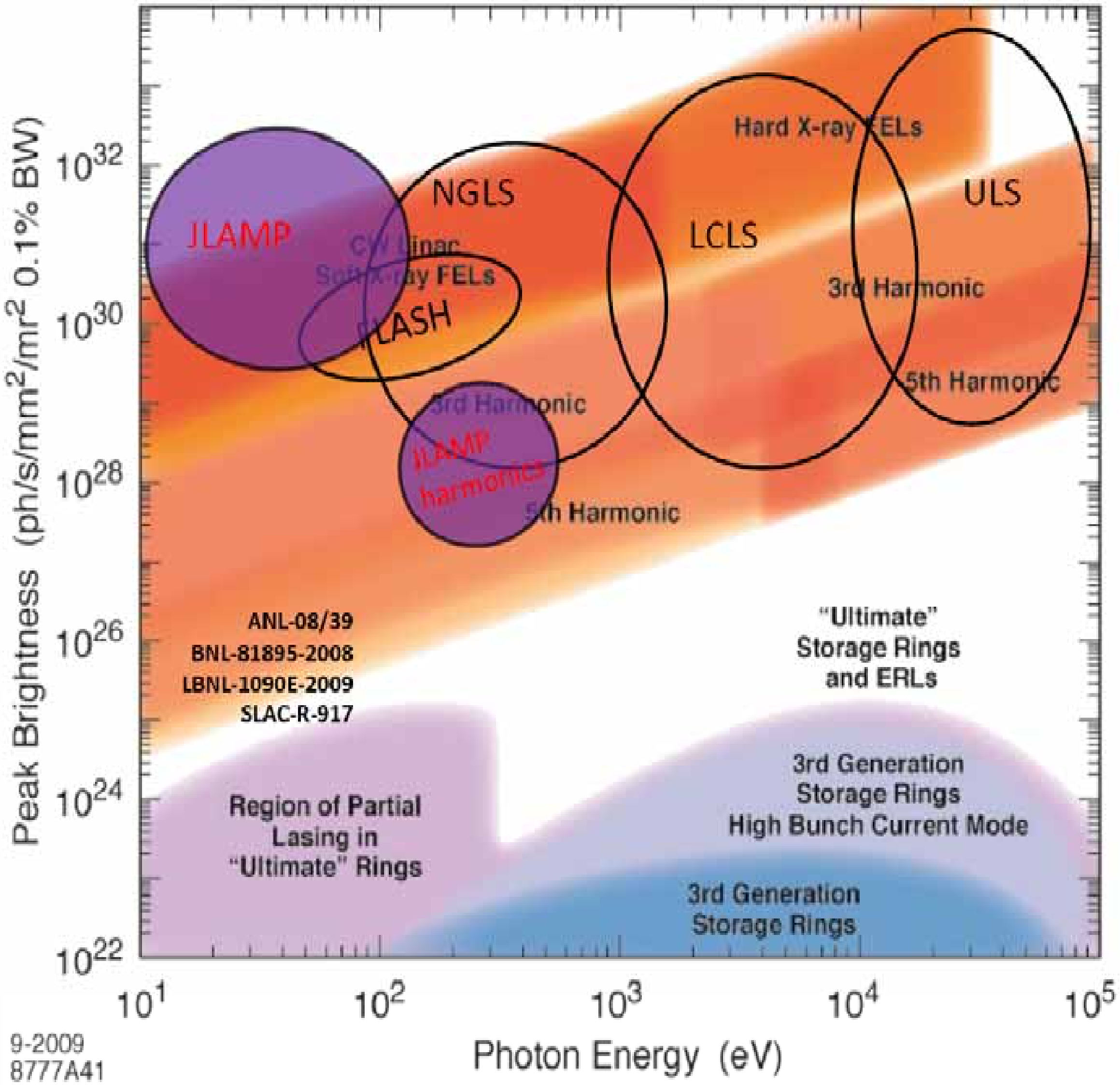
Next Generation Light Sources – International

1. FZR-Dresden, IR/THz, operational
2. Budker Institute, Novisibirsk, Russia, THz ERL operational
3. FLASH, Hamburg, Germany, soft x-ray, operational
4. Daresbury & Rutherford UK, THz-x-ray, prototype + NLS proposal
5. Paul Scherrer Inst. Switzerland, hard x-ray, proposal
6. Maxlab, Lund, Sweden, soft x-ray, proposal
7. XFEL, Hamburg Germany, hard x-ray, European project constr. phase
8. XFEL, Spring-8, Japan
9. Arc-en-Ciel, French ERL, proposal
10. XFEL, Pohang Light Source, Korea, proposal
11. IRFEL, Nijmegen, Netherlands, funded
12. IRFEL, Fritz-Haber Inst. Berlin, funded
13. Soft X-ray FEL, Berlin, discussions

Average Brightness Plot for Light Sources



Peak Brightness Plot for Light Sources



Science Drivers

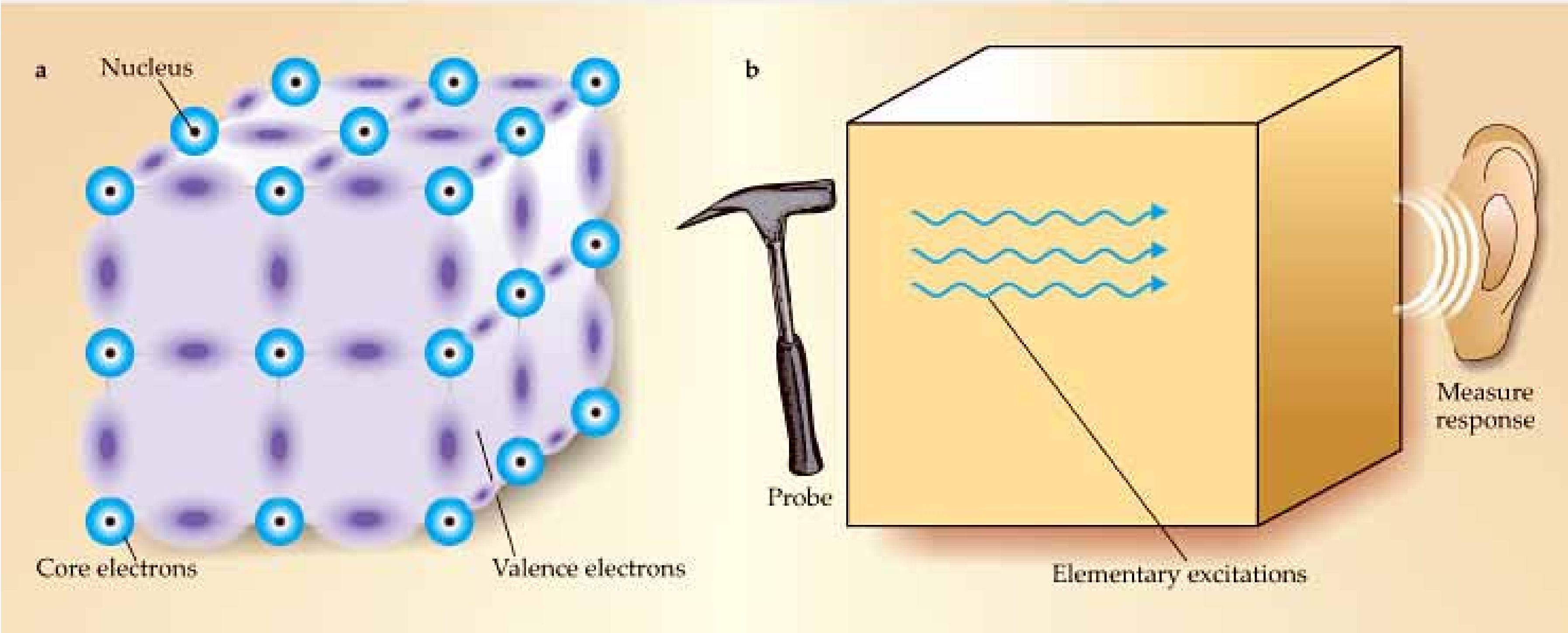
The behavior of many complex systems is not understood.

Examples: high Tc superconductors, giant magnetoresistive materials, nanomaterials, systems with complex charge order, correllated systems…..even excitations of simple atoms and molecules……

Need tools that study the complex interplay between electronic, spin, vibrational and phonon excitations.

Need to study systems in real-time and out of equilibrium and be able to selectively excite the electrons and phonons and watch the relaxation dynamics.

Another way of looking at it…….



reductionist approach
- electrons
- nuclei

emergence approach, collective excitations
- phonons,, magnons
- polarons, plasmons

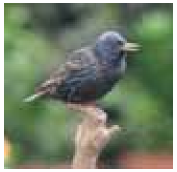
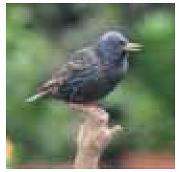
(called quasiparticles)

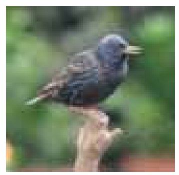
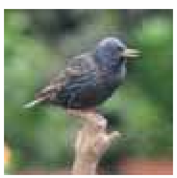
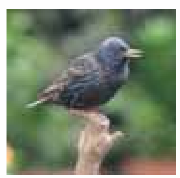
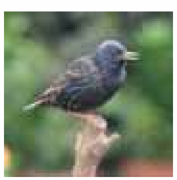
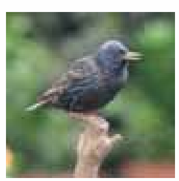
from Marvin Cohen, Physics Today, June 2006, page 48.

Simplicity – materials physics 1940 - 1985

Complexity – materials physics 1985 - present

Yet another way of looking at emergent behavior…….


Characteristic time scales of nature

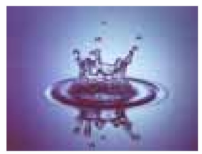
1 sec (1 s)

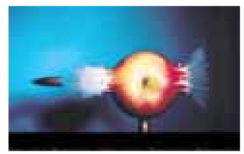
clock tick

1 millisecond (10^{-3} s)

camera shutter

1 microsecond (10^{-6} s)



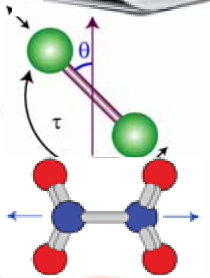


camera flash

1 nanosecond (10^{-9} s)

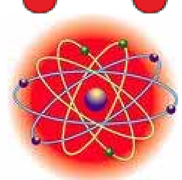
processor speed
data storage

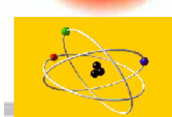
1 picosecond (10^{-12} s)



rotations
bond breaking
vibrations
charge transfer

1 femtosecond (10^{-15} s)





electron motions in atoms, molecules and materials

1 attosecond (10^{-18} s)

1 zeptosecond (10^{-21} s)

- Sub picosecond to attosecond pulses can capture all motion in the natural world, even at the level of electrons

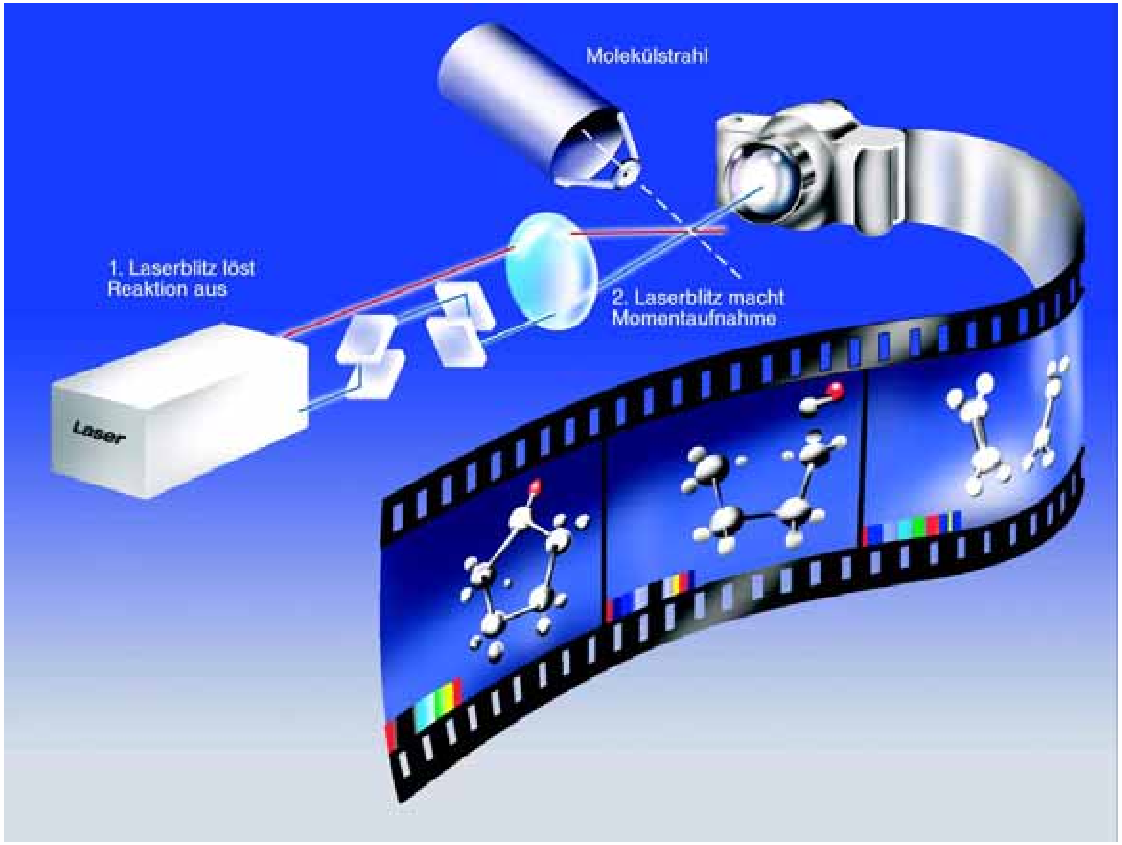
It’s all about fast and small……

Atomic resolution, with femtosecond frame rates…..

Electronic and phonon excitations……

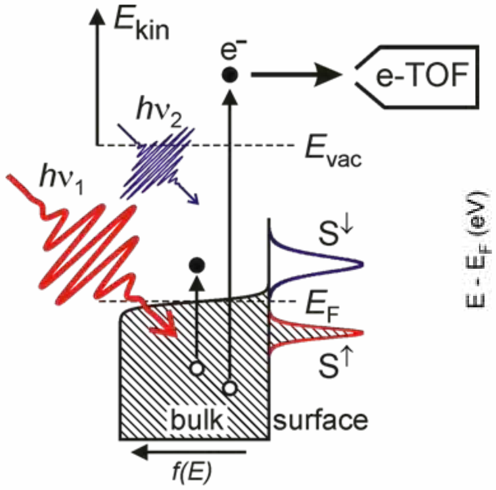
Need ultrafast x-ray laser……JLAMP

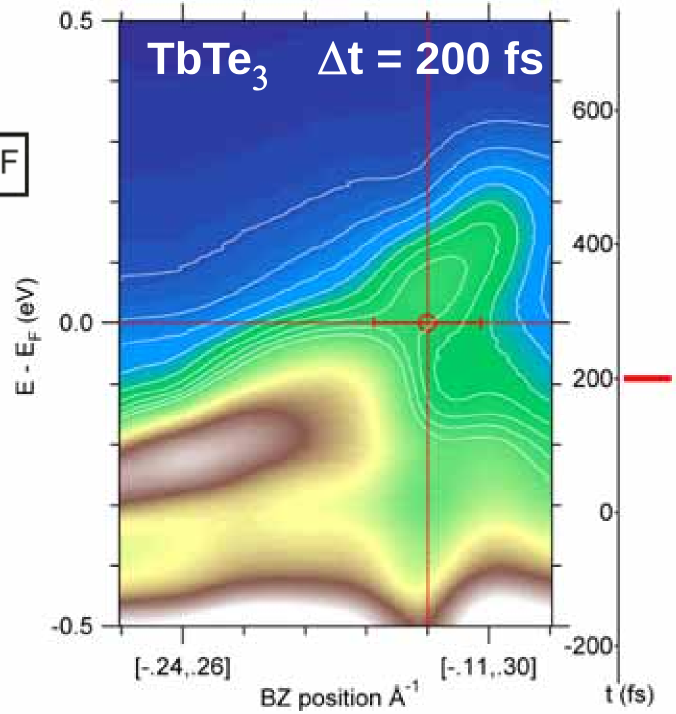
Movies of chemical reactions



…aka… ultrafast dynamics

Materials Science



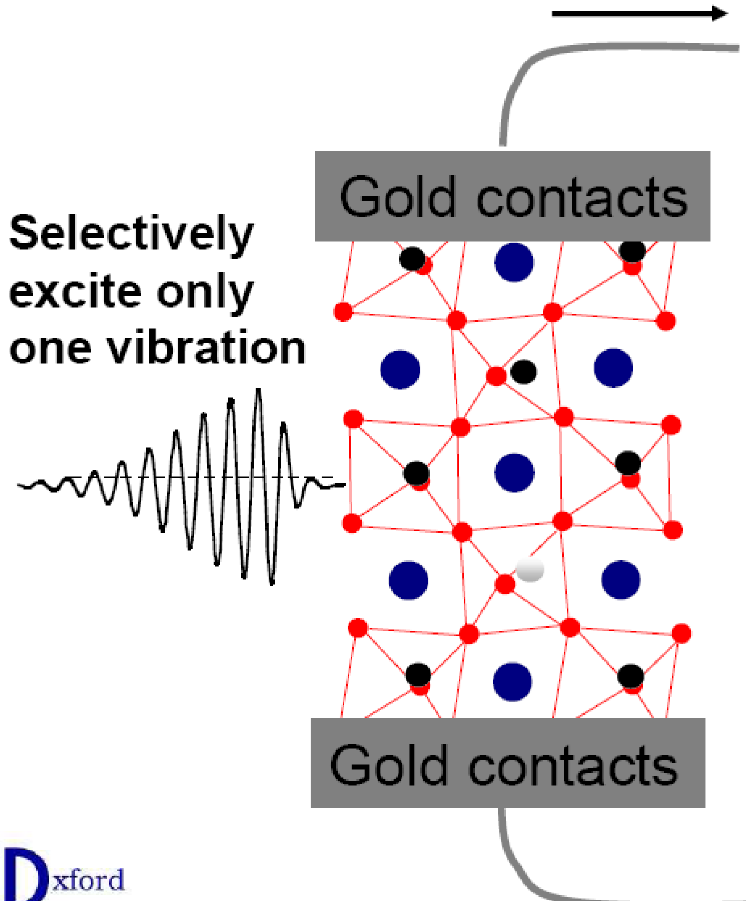


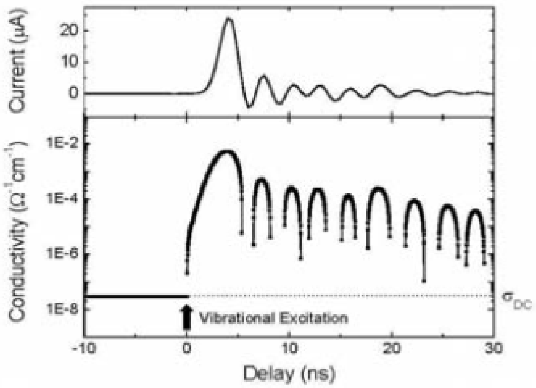
Energy and momentum resolved snapshot of the electronic structure of the charge density
wave system $TbTe_3$ at a time-delay of 200 fs after photoexcitation
*[F. Schmitt et al., Science **321**, 1649 (2008)].*

THz control of metal/insulator transition

manganite material

Selectively excite only one vibration

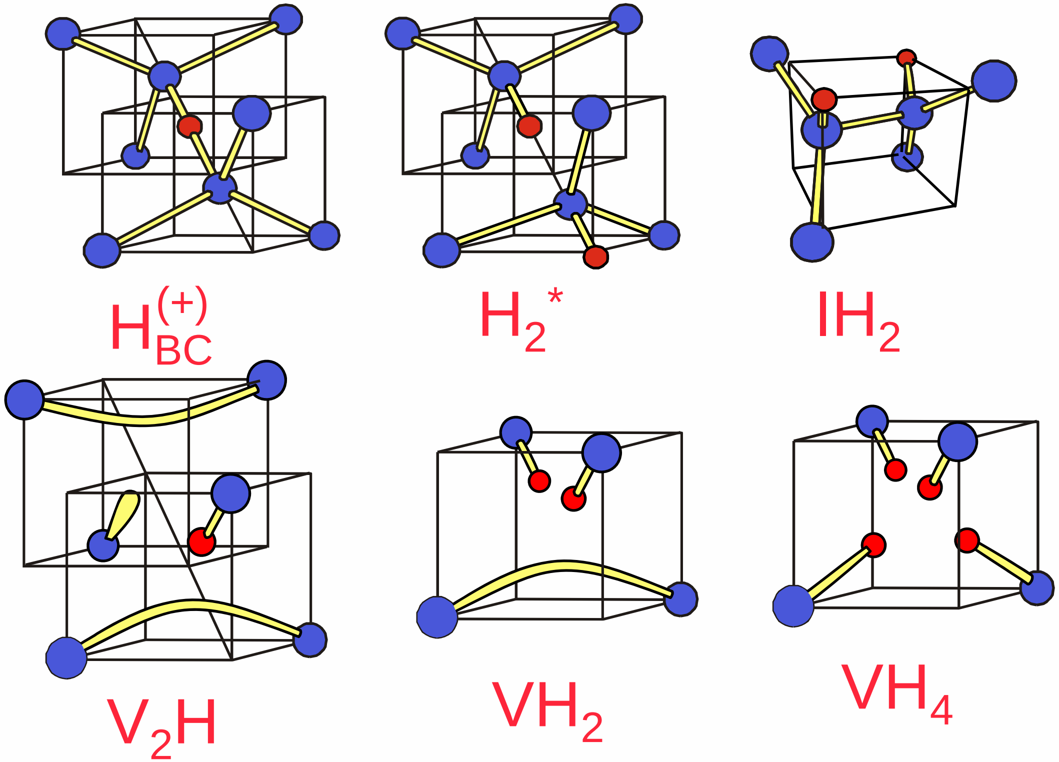




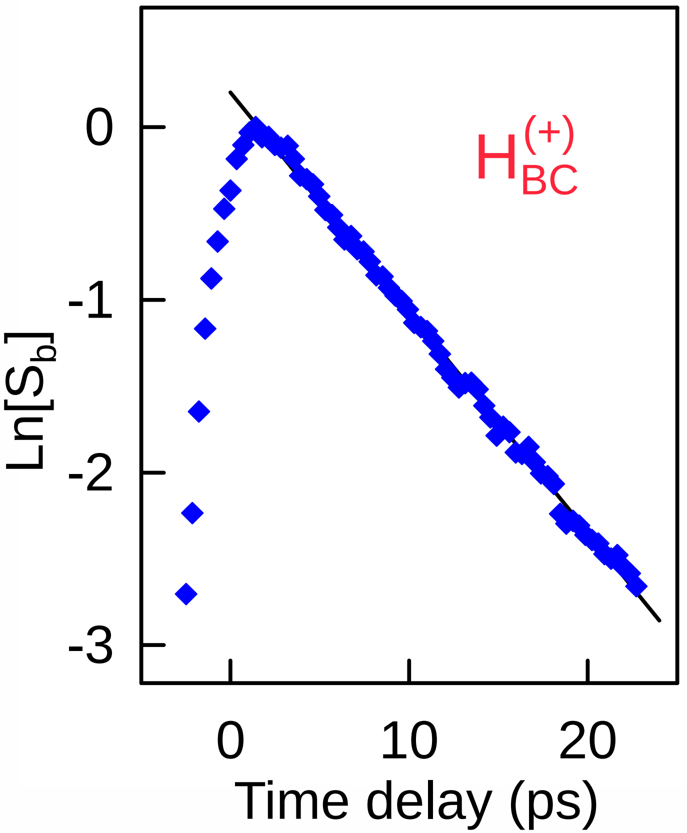
Cavalleri et al, Nature 449 72 (2007)

Example from existing JLab FEL

Defect Dynamics



Luepke et al. CWM/Vanderbilt



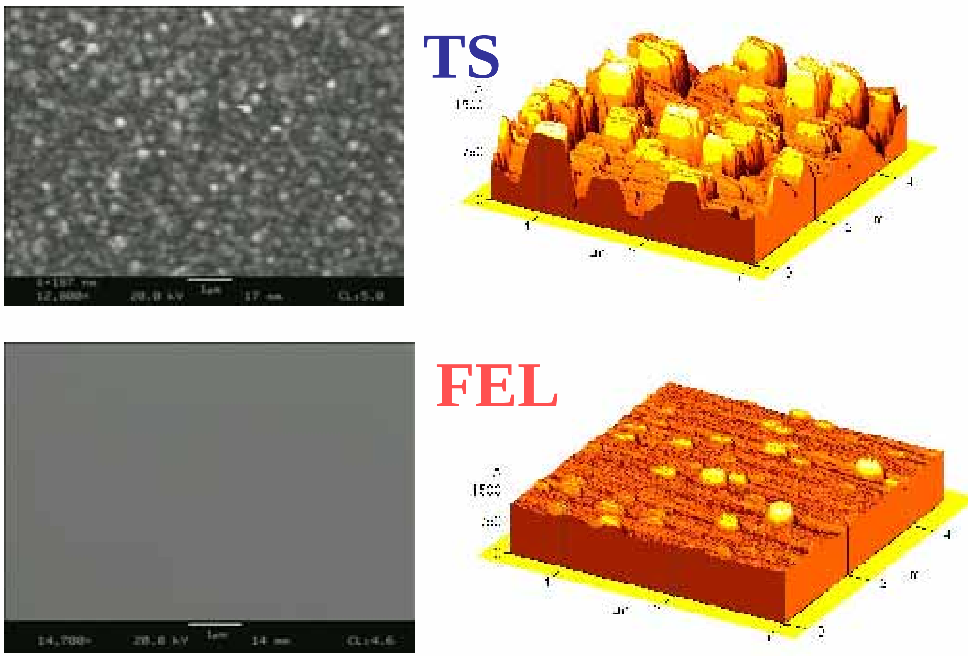
Luepke et al. Phys. Rev. Letts **85**, 1452 2000
Wm. & Mary Phys. Rev. Letts **88**, 135501, 2002
Vanderbilt Phys. Rev. Letts **87**, 145501, 2001
Phys. Rev. **B63** 195203 2001
J. Appl. Phys. **93** 2316, 2003

$T_1 = 7.8 \pm 0.2$ ps

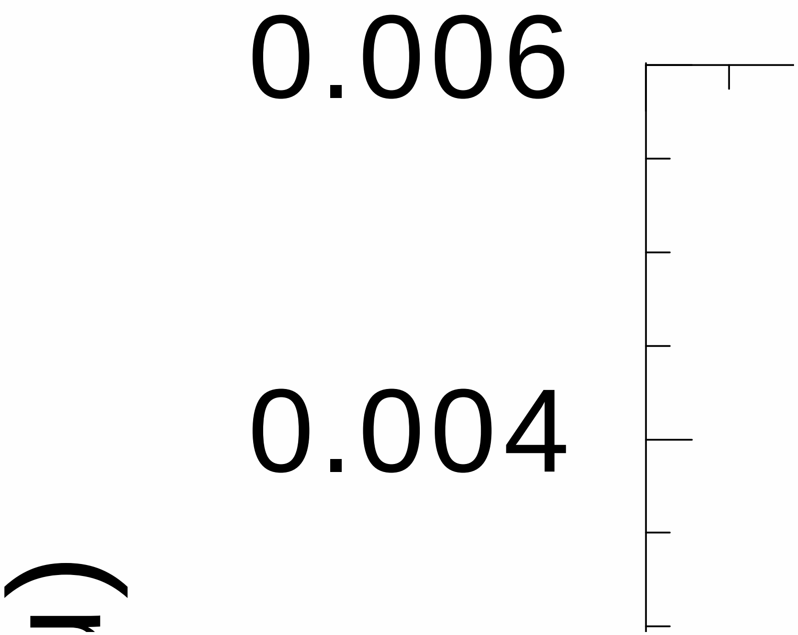
JLab FEL – making new materials…

Pulsed laser deposition of $Ni_{80}Fe_{20}$ "Permalloy" films with the JLab-FEL

A. Reilly et al. CWM
J. Appl. Phys. 95 3098 (2003)



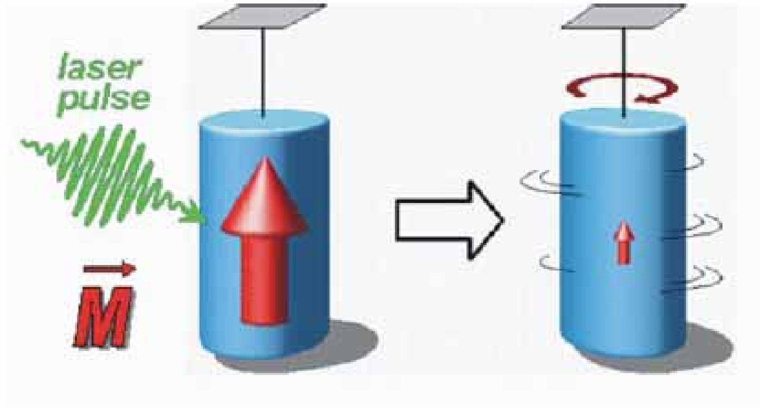
SEM **AFM**

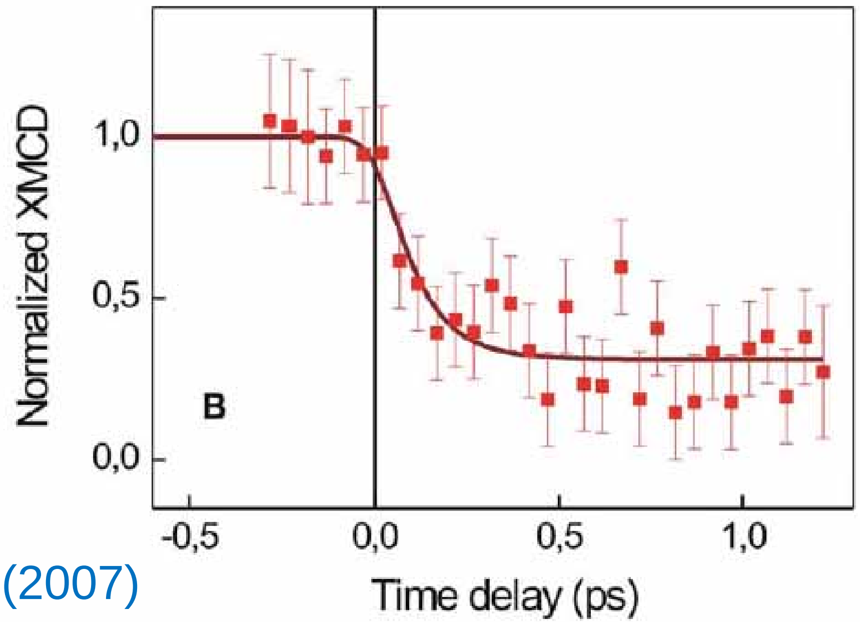


Magnetic Hysteresis

Magnetic storage dynamics……….

New science – tunable electronic excitations….





Eberhardt et al.
Nature Materials **6** 740 (2007)

Tunable electronic excitations….

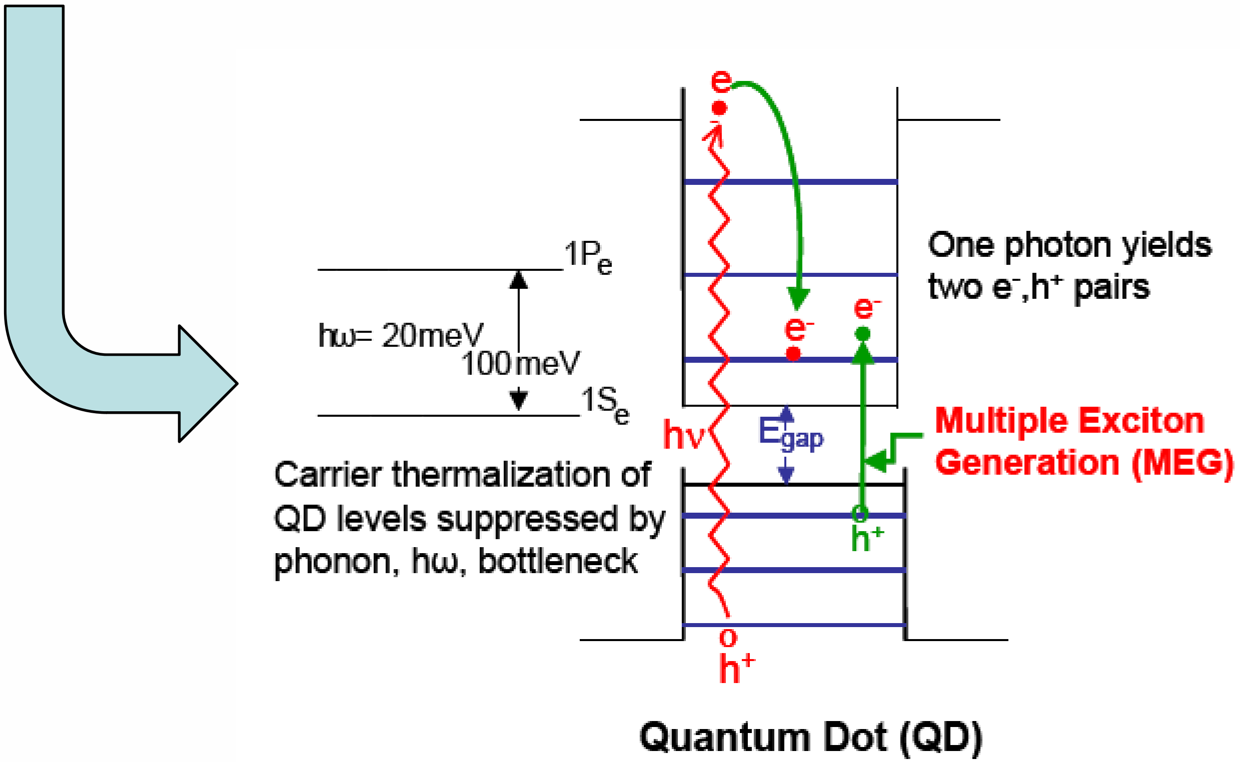
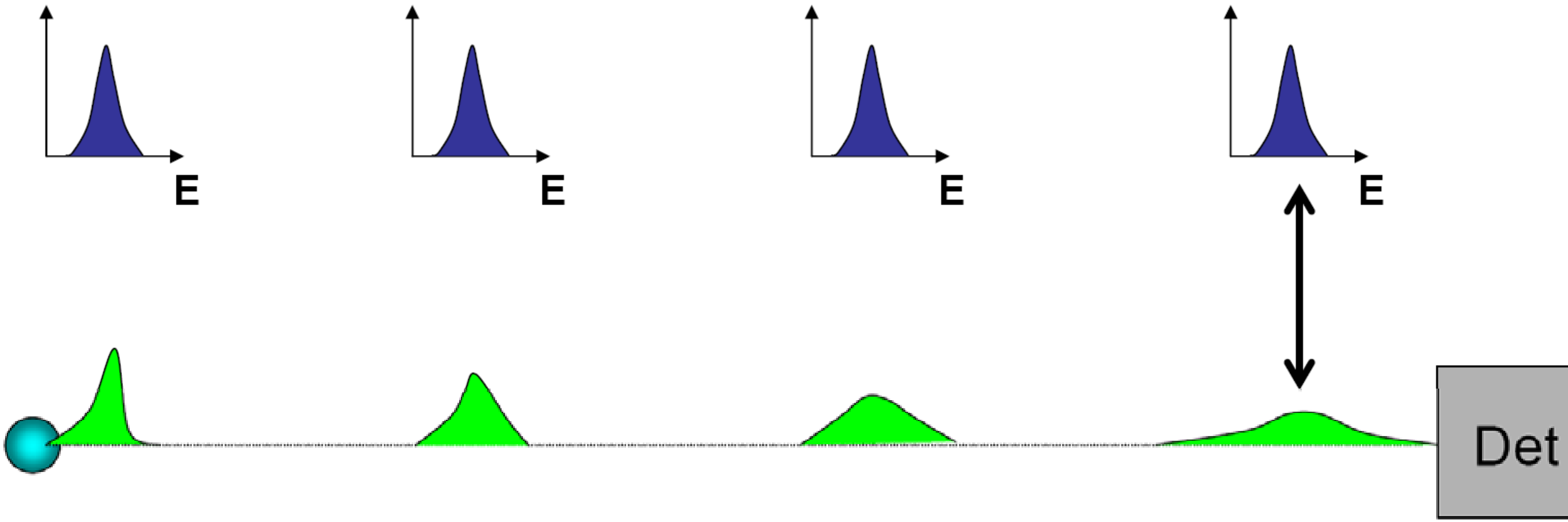


Figure 1 In quantum dots used for solar cell applications, the absorption of one incident photon can lead to the creation of more than one electron-hole pair. A.J. Nozik, Physica **E14 115** (2002)

Wave packet-dispersion
→ no time-information at detector



Vacuum is a dispersive medium for matter

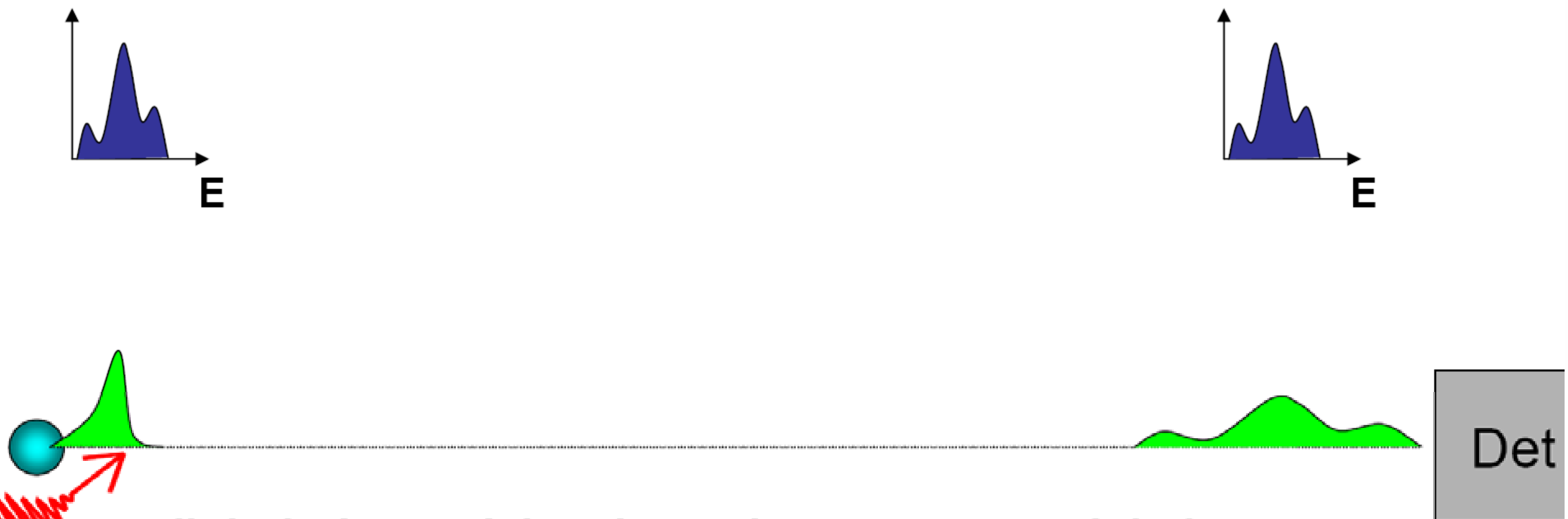
→ wave packet dissolves upon propagation

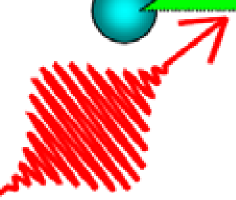
→ at detector the wave-packet maps *velocity*-distribution,

not original *temporal* evolution !

From Markus Drescher

Capturing a wave-packet <u>during</u> its formation





light induces delay-dependent energy modulation, that survives propagation

requires:

- **short ionizing pulse**
- **synchronized light-field** *(duration does not matter)*
- **mechanism for energy-modulation**

From Markus Drescher

Example 3 – AMO, encoding the wavefunction

August 23, 2009

ARTICLES NATURE PHOTONICS DOI: 10.1038/NPHOTON.2009.160

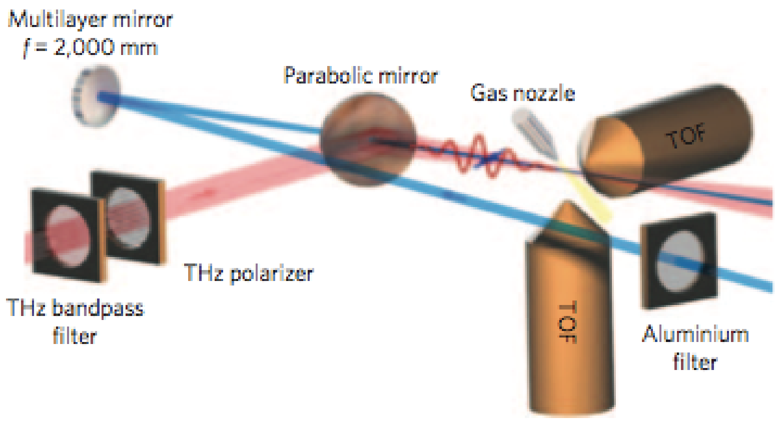
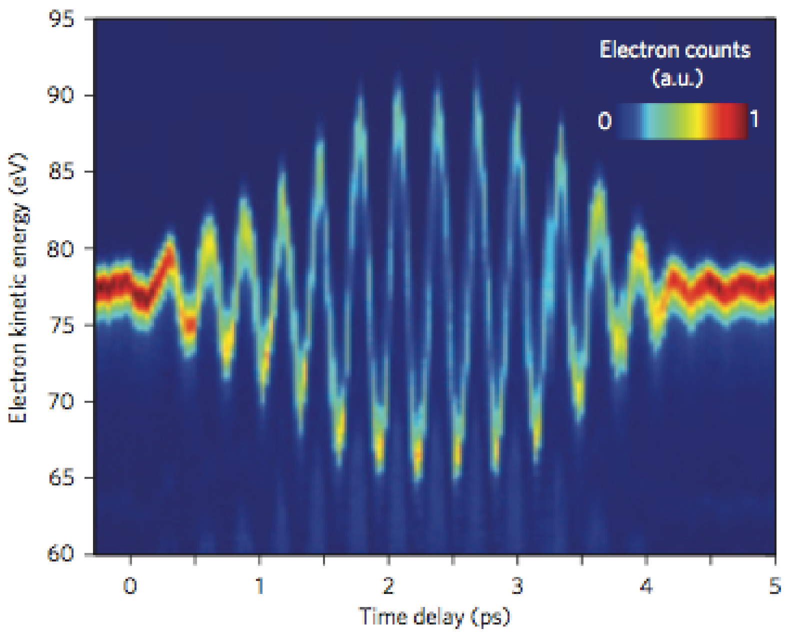


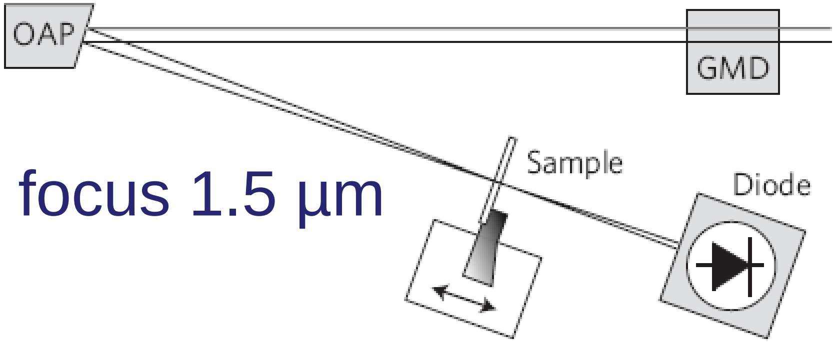
Figure 1 | Schematic of the experimental setup. Horizontally polarized soft X-ray (blue beam) and vertically polarized terahertz (red beam) pulses are focused and collinearly superimposed in a krypton gas target. Photoelectrons are detected with two time-of-flight (TOF) spectrometers, one parallel and one perpendicular to the terahertz polarization. A terahertz bandpass filter is used to narrow and smooth the terahertz spectrum. An aluminium filter is used to reduce the soft X-ray intensity.



Kr 2p

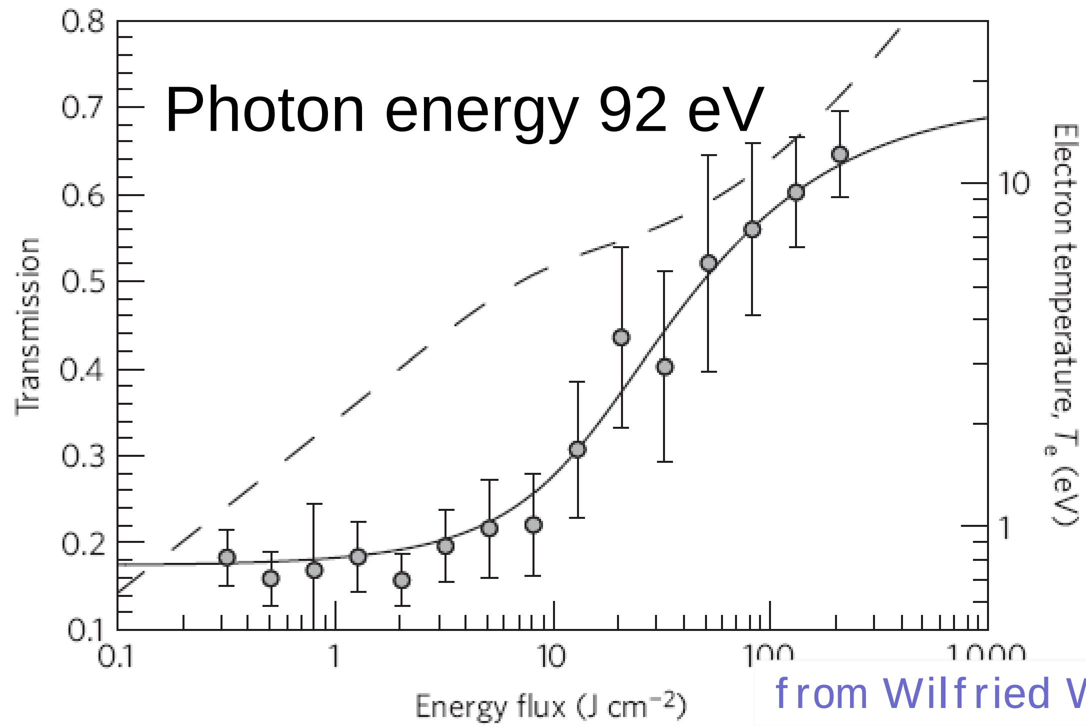
Figure 2 | Sampled terahertz vector potential. Series of kinetic energy spectra of 4*p* photoelectrons detached from krypton atoms by a 13.5-nm soft X-ray pulse in the presence of an intense pulsed terahertz field (false-colour representation). The energy shift of the electrons versus the X-ray/terahertz delay directly represents the vector potential A_{THz}.

FLASH, DESY – Transparent aluminium



focus 1.5 µm

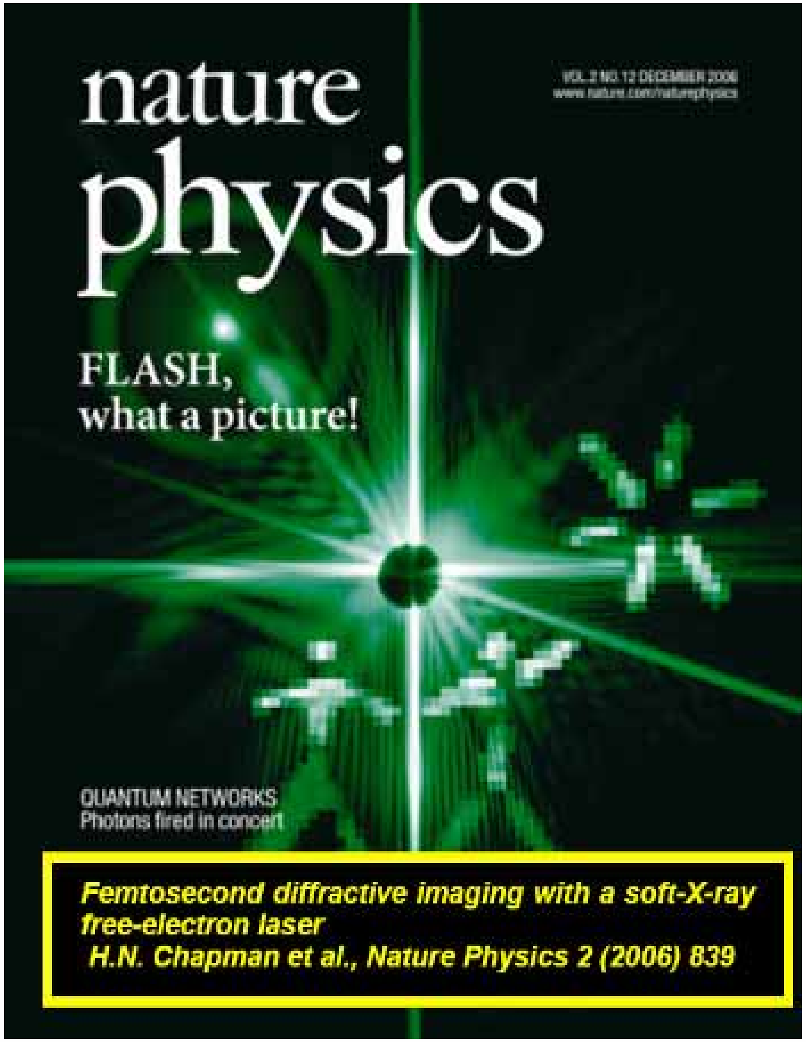
Saturated absorption for a core transition !
Every Al atom with an L-shell hole



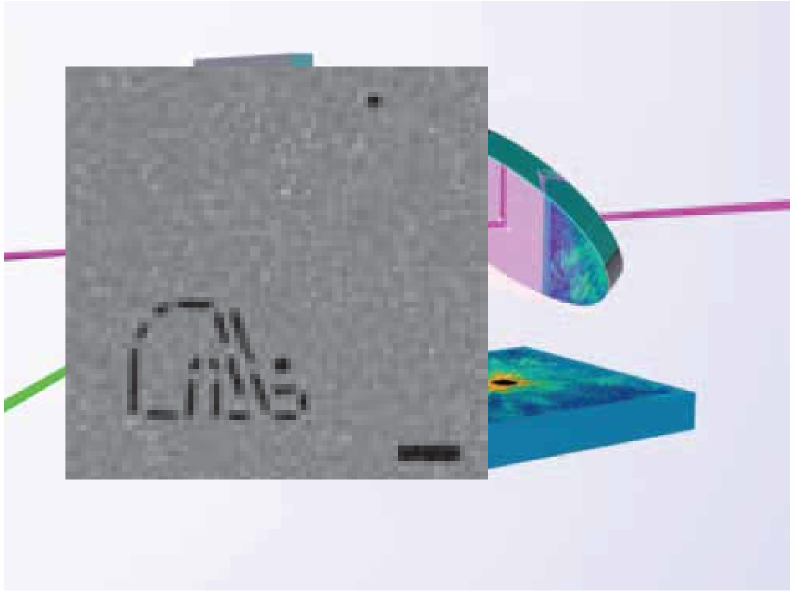
from Wilfried Wurth

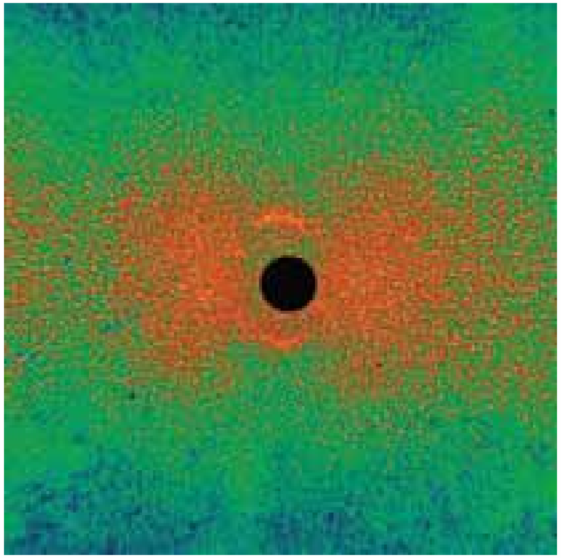
Peak brightness collab.: Bob Nagler et al., Nature Physics **5**, 693 (2009)

FLASH, DESY - Lensless imaging

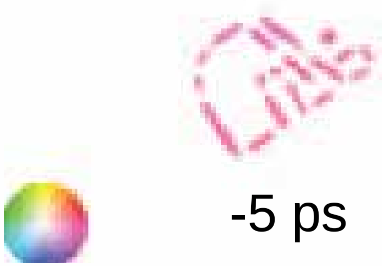


Ultrafast single-shot diffraction imaging of nanoscale dynamics

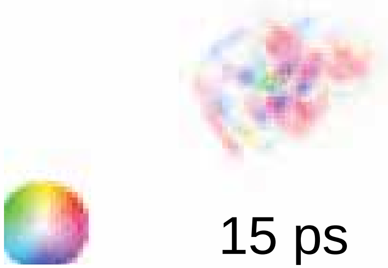




Time sequence -5ps to 140 ps



-5 ps

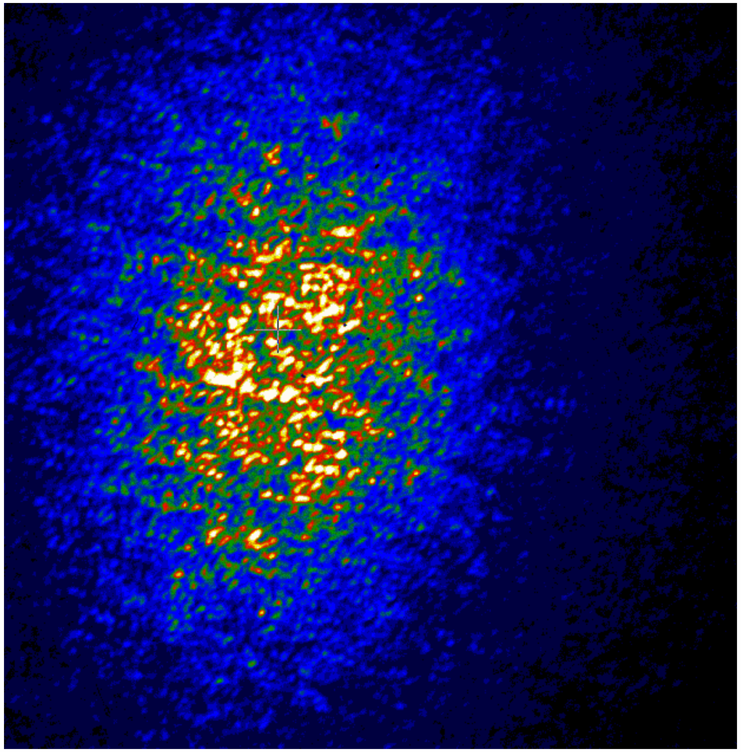


15 ps

Jefferson Lab

A. Barty et al., *“Ultrafast single-shot diffraction imaging of nanoscale dynamics”,* Nature Photonics 2, 415–419, (2008)

Resonant Inelastic X-ray Scattering (RIXS)

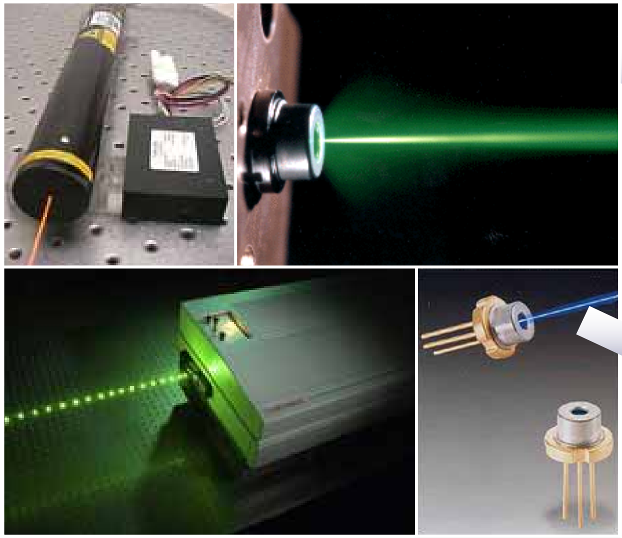


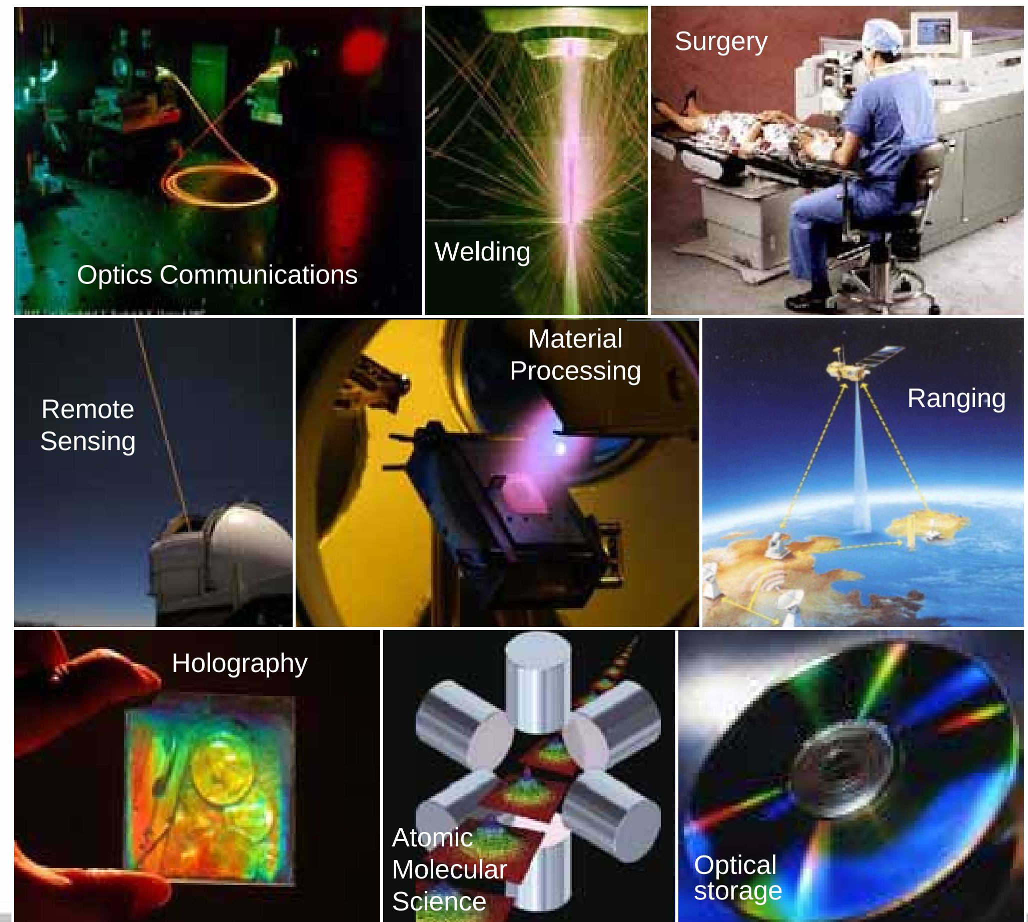
Coherent diffraction pattern from orbital order in a doped manganite, $Pr_{0.5}Ca_{0.5}MnO_3$
J. Turner et al. N. J. of Phys. ***10****, 053023 (2008).*

The tools of the trade……

- next gen light sources

Visible laser light has greatly benefitted society

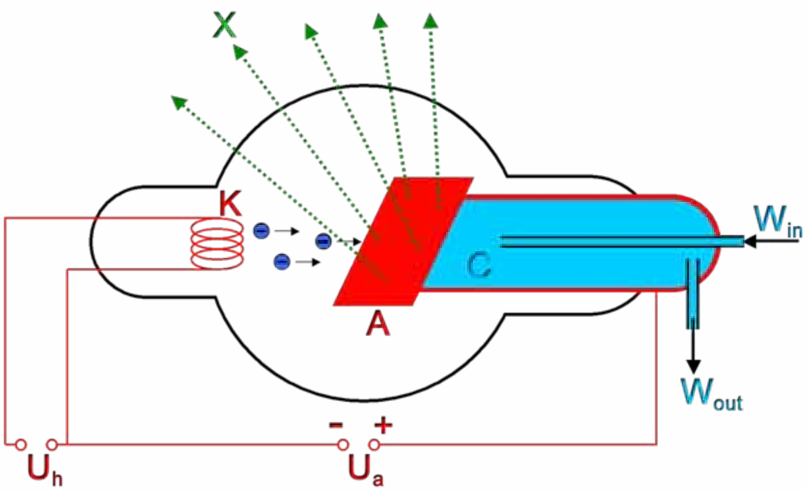




from Margaret Murnane

X-ray light also greatly benefits society

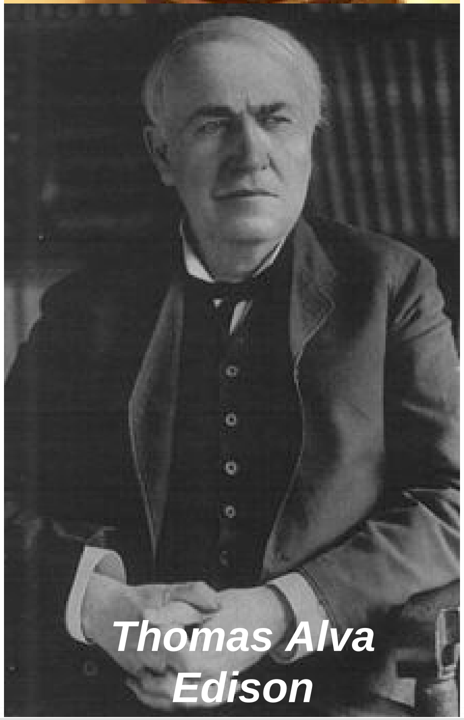
Wilhelm Roentgen



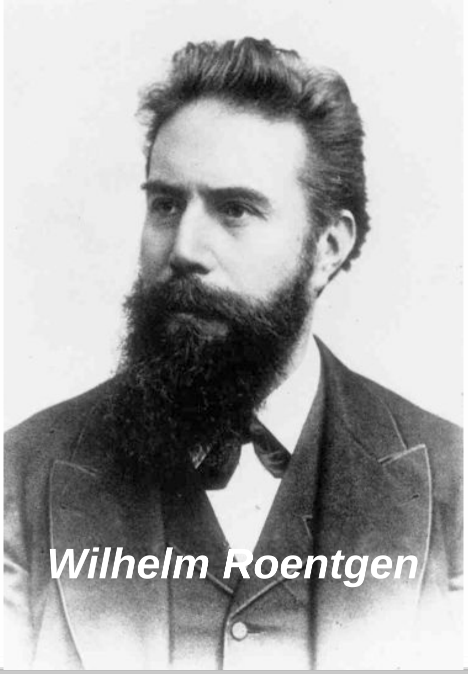
X-ray tube

from Margaret Murnane

Incoherent radiation

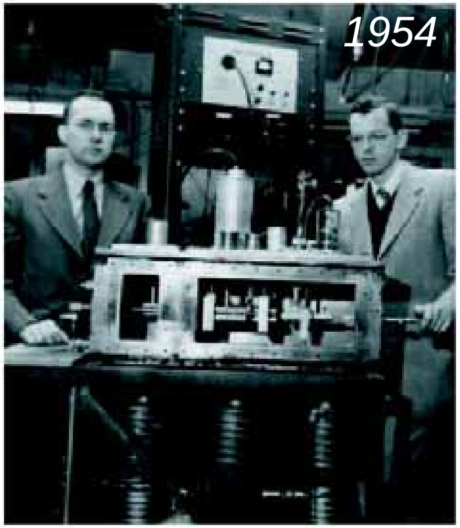


17 years later………

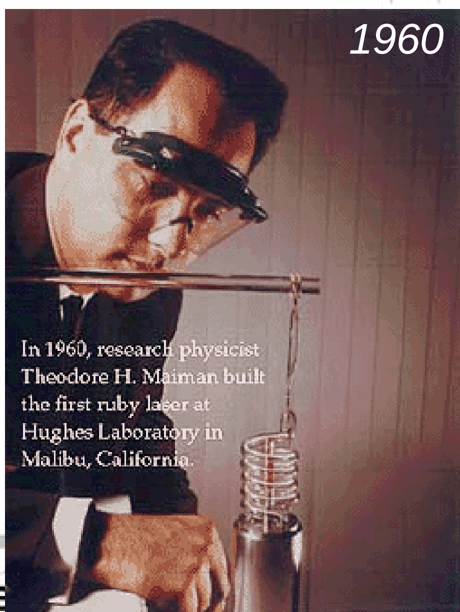


from Margaret Murnane

Coherent laser radiation

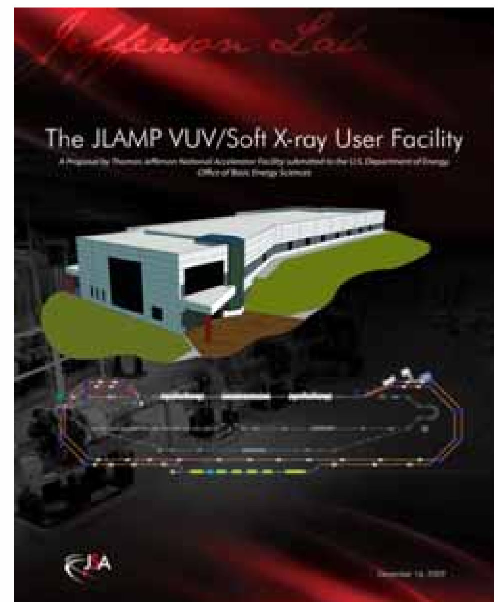


Townes and Gordon with one of their first masers (1954).



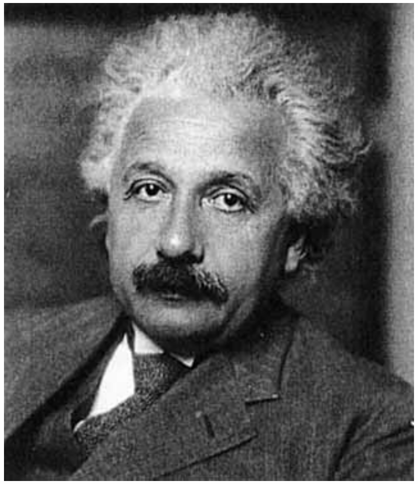
50 years later………

LCLS



from Margaret Murnane

Why are x-ray lasers so challenging to build?



Spontaneous emission / Stimulated emission

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \propto \nu^3$$

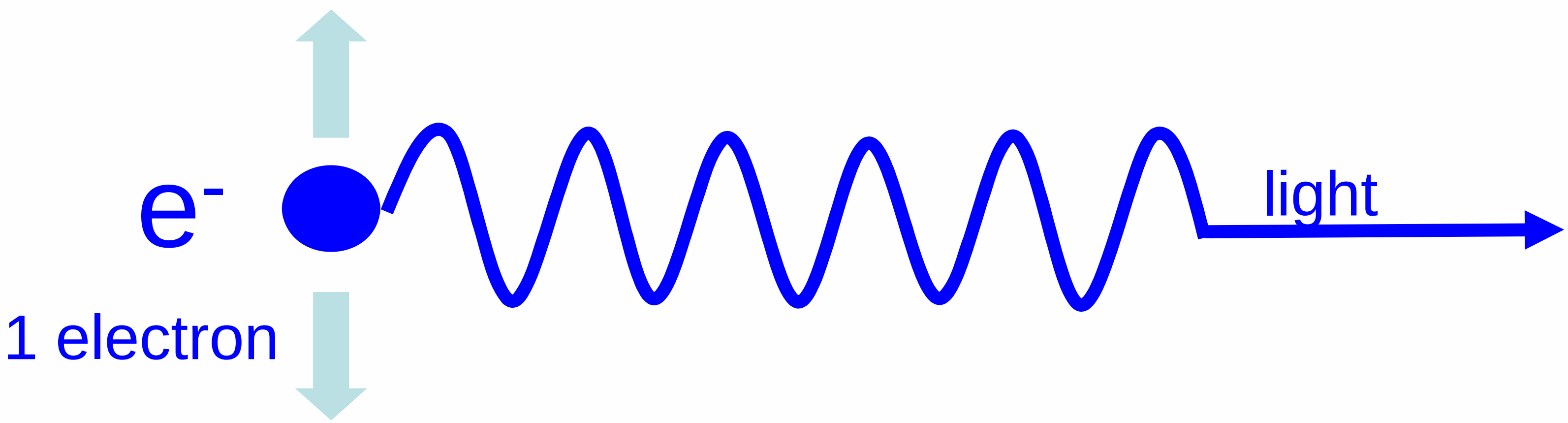
$$Power \propto \left(\frac{1}{\sigma_g}\right)\left(\frac{1}{\tau}\right)(h\nu) \propto \frac{1}{\lambda^5}$$

- 1 μm -> 1 mW
- 1 nm -> TW
- 1 Å -> 1 PW

from Margaret Murnane

Multiparticle Coherent Synchrotron Radiation

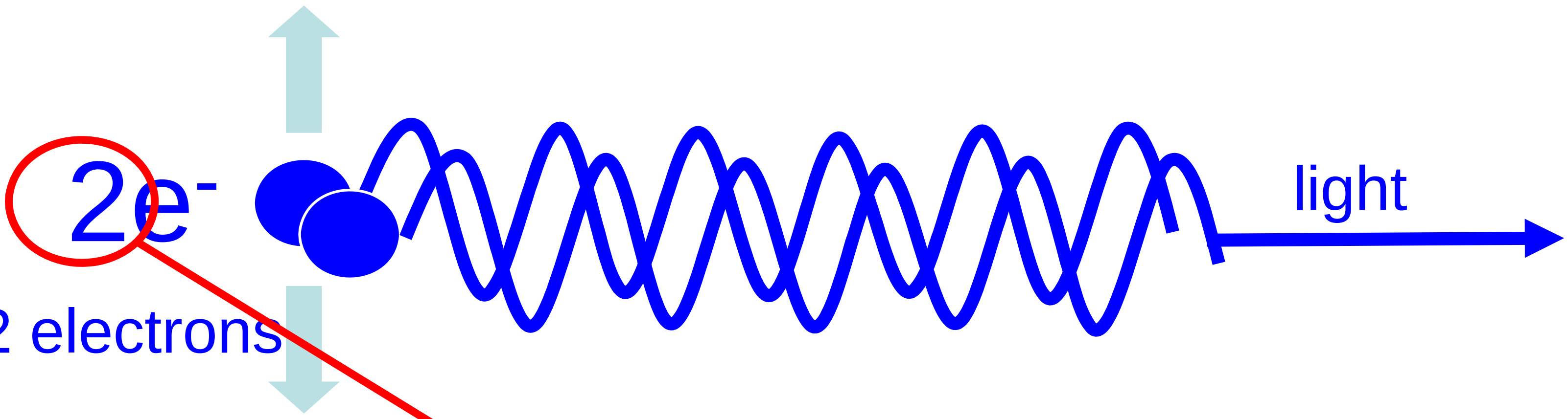
………aka longitudinal coherence



Larmor's Formula: $\text{Power} = \dfrac{2(\;\;e)^2 a^2 \gamma^4}{3c^3}$ (cgs units)

Multiparticle Coherent Synchrotron Radiation

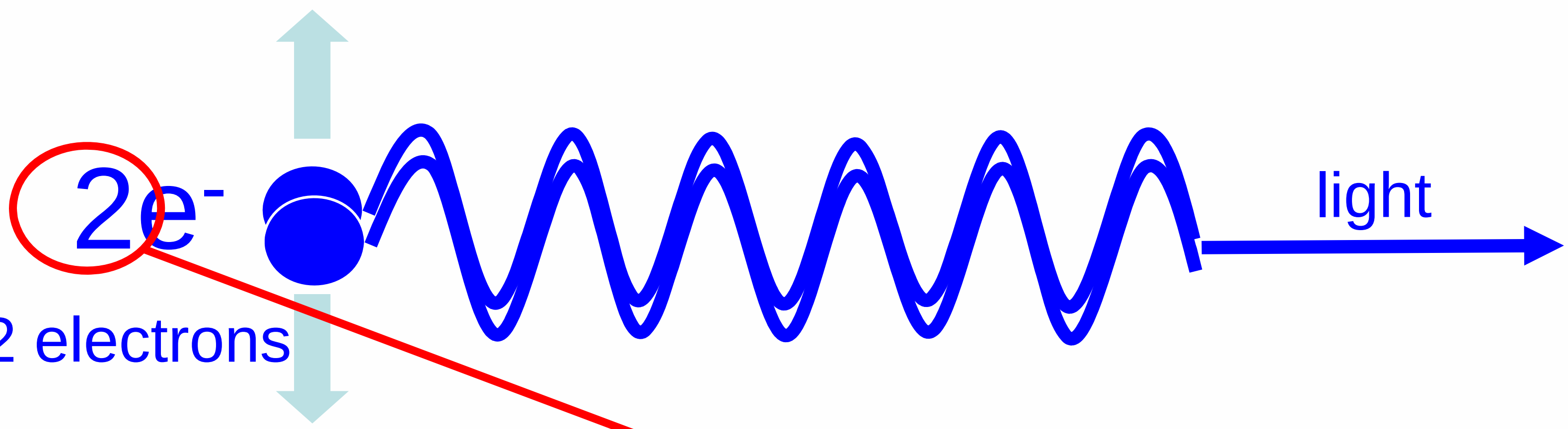
………aka longitudinal coherence



Larmor's Formula: $\text{Power} = 2\left(\frac{2(e)^2 a^2 \gamma^4}{3c^3}\right)$ (cgs units)

Multiparticle Coherent Synchrotron Radiation

………aka longitudinal coherence

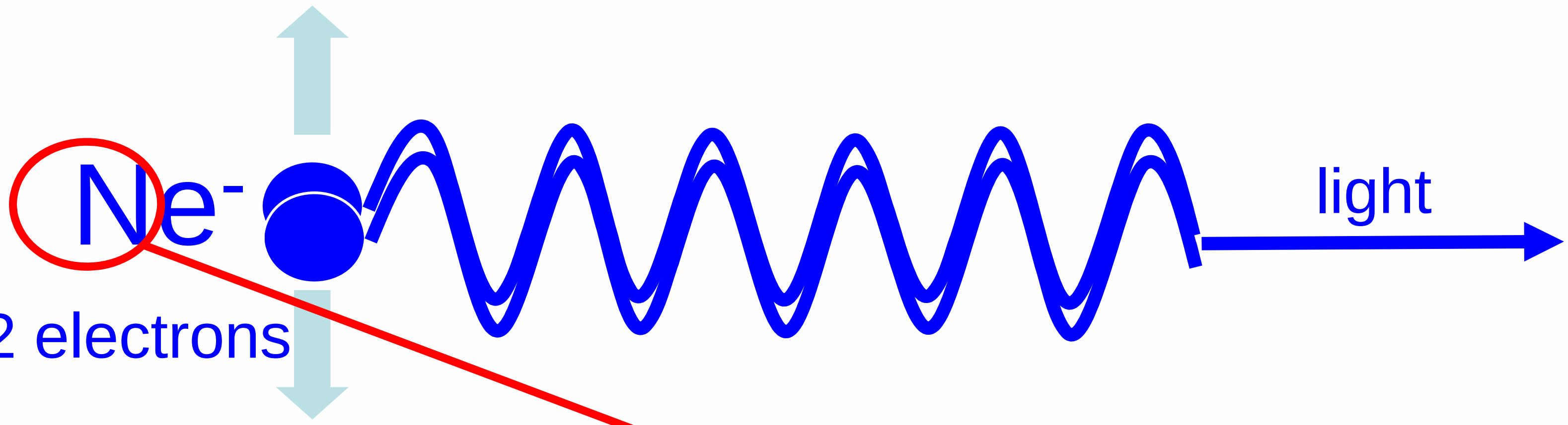


Larmor's Formula: $\text{Power} = \left(\frac{2(2e)^2 a^2 \gamma^4}{3c^3}\right)$ (cgs units)

So 2 electrons give 4 times the power of 1 electron

Multiparticle Coherent Synchrotron Radiation

………aka longitudinal coherence



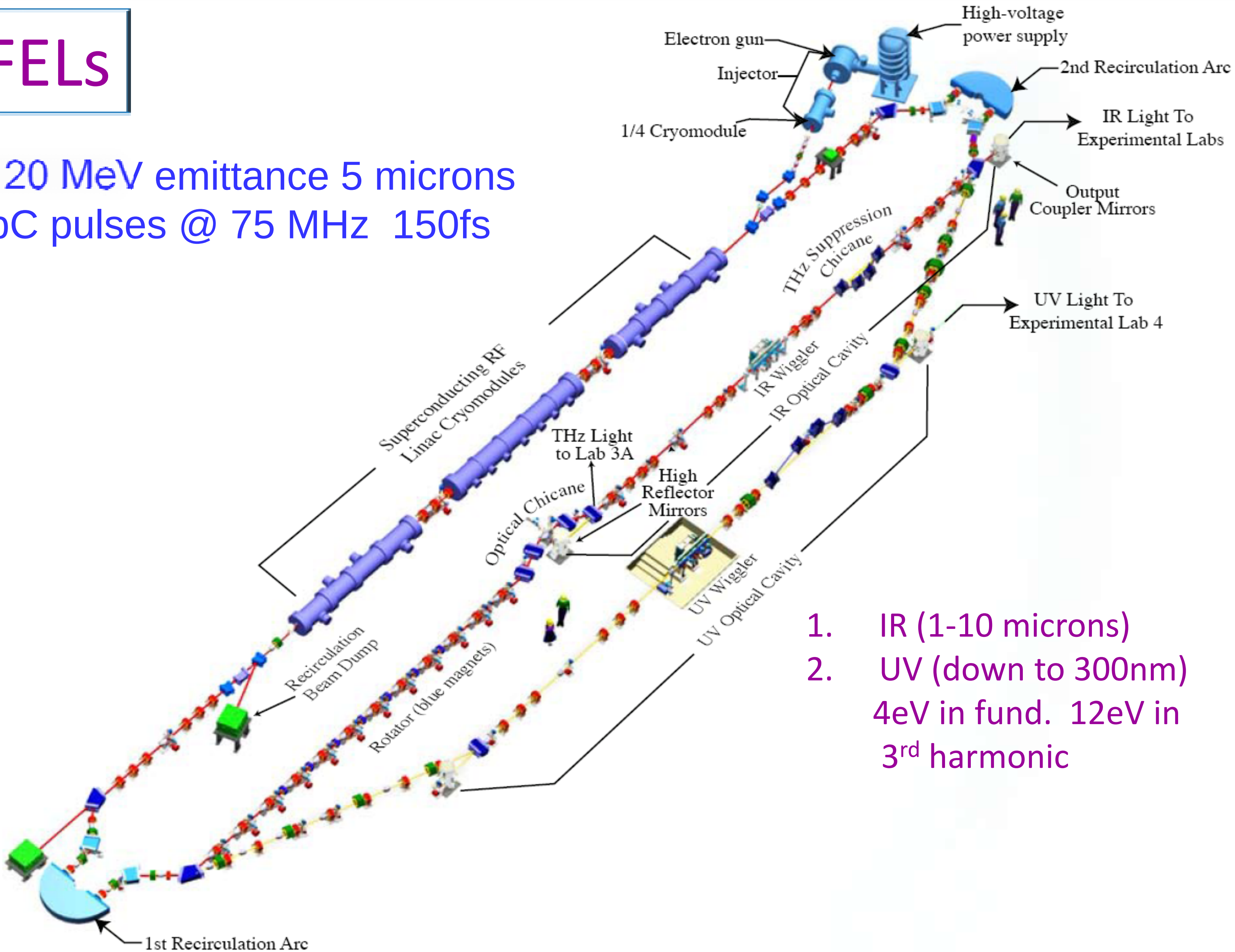
Larmor's Formula: $\text{Power} = \left(\dfrac{2(N\,e)^2 a^2 \gamma^4}{3c^3} \right)$ (cgs units)

So N electrons give N^2 times the power of 1 electron

JLab's Existing IR/UV 4th Generation Light Source

2 FELs

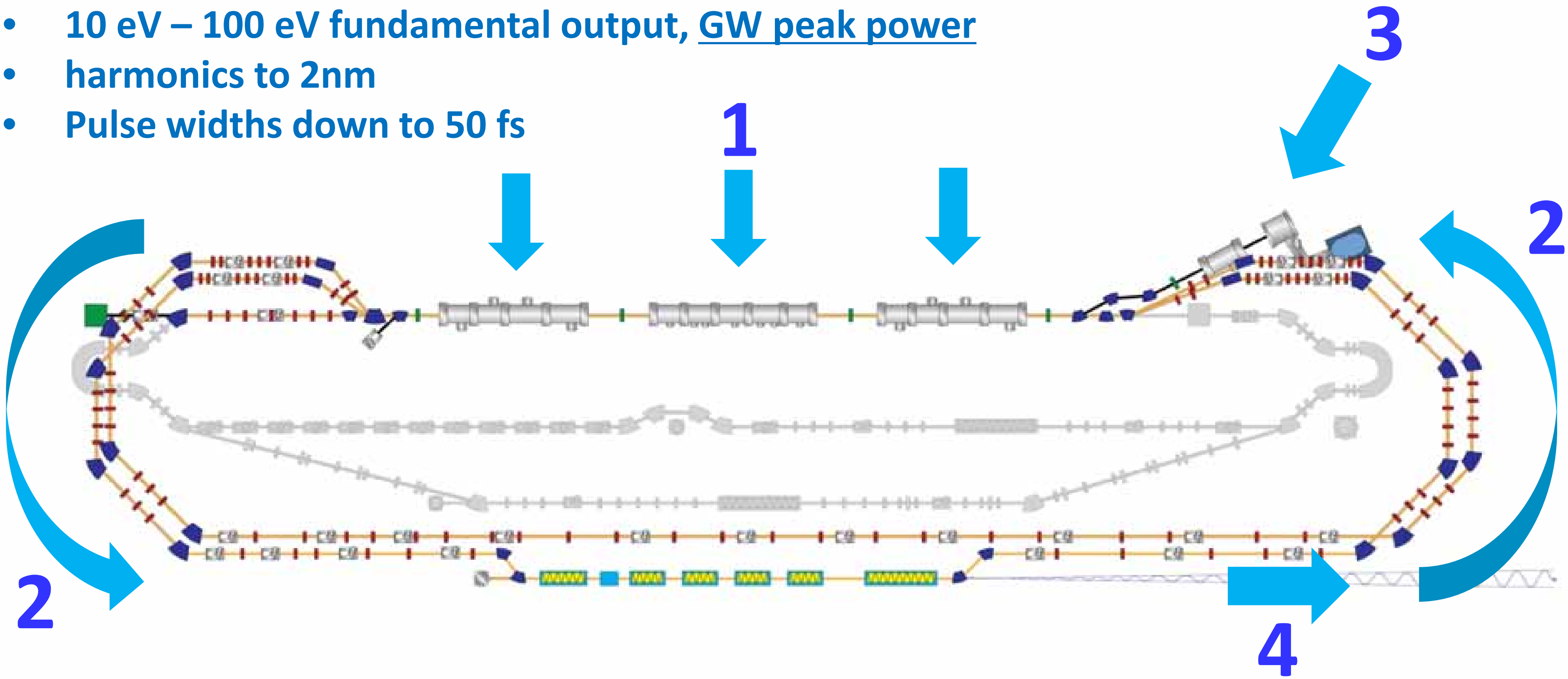
E = 120 MeV emittance 5 microns
135 pC pulses @ 75 MHz 150fs



1. IR (1-10 microns)
2. UV (down to 300nm) 4eV in fund. 12eV in 3rd harmonic

JLab Conversion to JLAMP

- 4 steps
- 600 MeV, 2 pass acceleration
- 200 pC, 1 mm mrad injector
- Up to 4.68 MHz CW repetition rate
- Recirculation and energy recovery
- 10 eV – 100 eV fundamental output, GW peak power
- harmonics to 2nm
- Pulse widths down to 50 fs



Conclusion

DOE-BES have identified science drivers and tools.

We have submitted a $96M proposal for JLAMP.

We would very much like to work with PNNL on science and also tool development.

The Jefferson Lab FEL Team

This work supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the DOE Air Force Research Laboratory, The US Army Night Vision Lab, and by DOE under contract DE-AC05-060R23177.