Energy Recovery Linac Experimental Challenges

CHESS & LEPP

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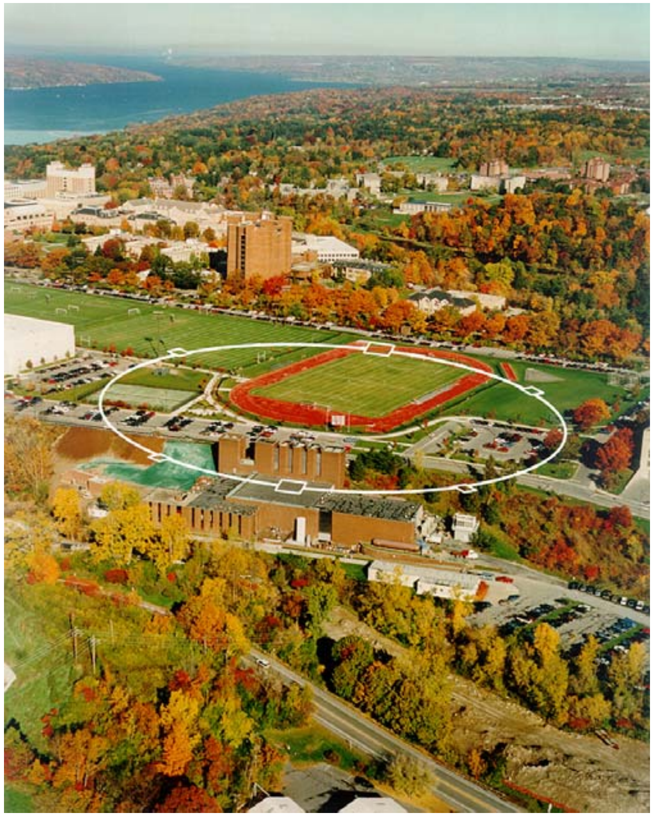
1. **Introduction to ERLs**
2. **Start with ERL layout + x-ray beam lines**
3. **Look at machine features**
4. **Look at the x-ray experiments**
5. **Add up the challenges – they are many!**
6. **Conclusions**



*for the ERL/LEPP/Chess developers team

ERL Overview

- **Energy Recovery Linac (ERL) light source projects at Jlab (IR FEL), Daresbury (4GLS), KEK and Cornell**

- **Use CU ERL as an example of experimental challenges on the user end.**

Cornell ERL Layout

(current version, layout still under development)

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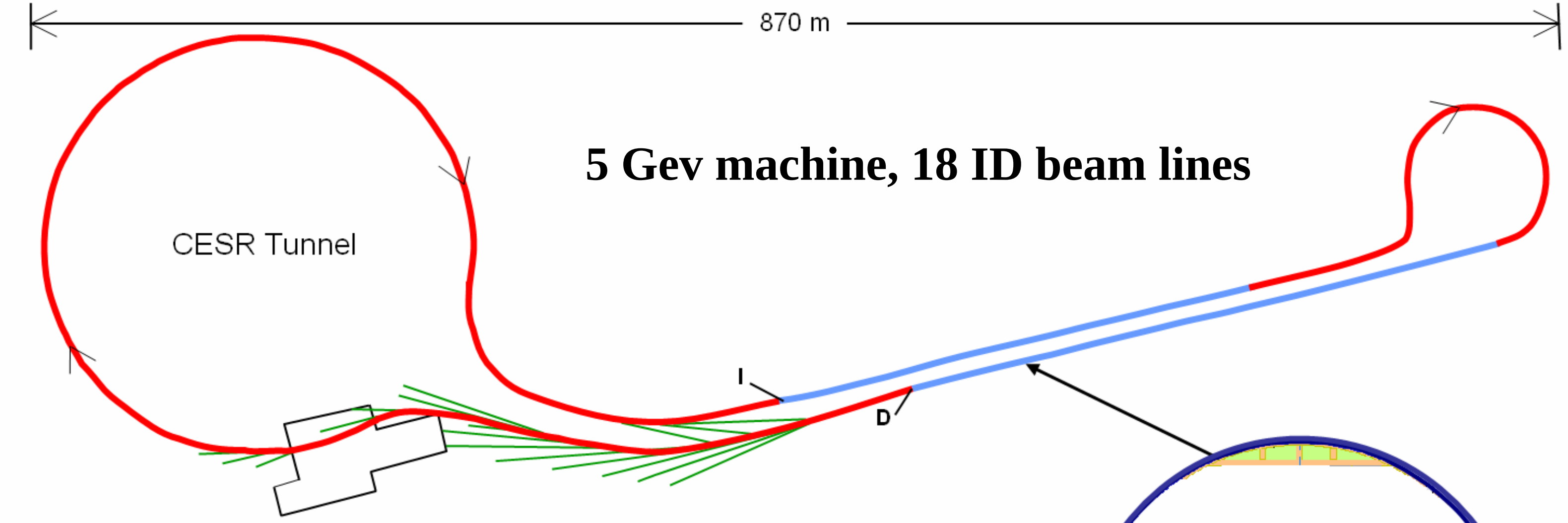
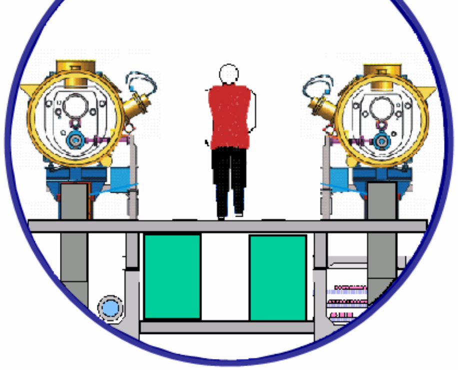


5 Gev machine, 18 ID beam lines

Preliminary layout view of an ERL upgrade to CHESS in the present CESR tunnel. A new tunnel with a return loop will be added to CESR. Electrons are injected into superconducting cavities at (I) and accelerated to 2.5 GeV in the first half of the main linac, then to 5 GeV in the second half. The green lines show 18 possible beamline locations. Electrons travel around the CESR magnets clockwise and re-enter the linac out of phase. Their energy is extracted and the spent electrons are then sent to the dump (D).



Two superconducting linacs in one tunnel accelerate the electrons to 5 GeV. Person shown for scale.

__3 Basic Operating Modes__

Hi-flux: 30 pm emittance, 100 mA, 77 pC, 1300 MHz repetition rate
electron energy spread of 2E-4 (5 pm, 100 mA long-term goal)

Hi-coherence: 8 pm, 25 mA, 7.7 pC, (5 pm, 100 mA long-term goal)

Ultra-fast: 511 pm, 1 mA, 1 nC, 1 MHz repetition rate

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Hi-flux opportunity

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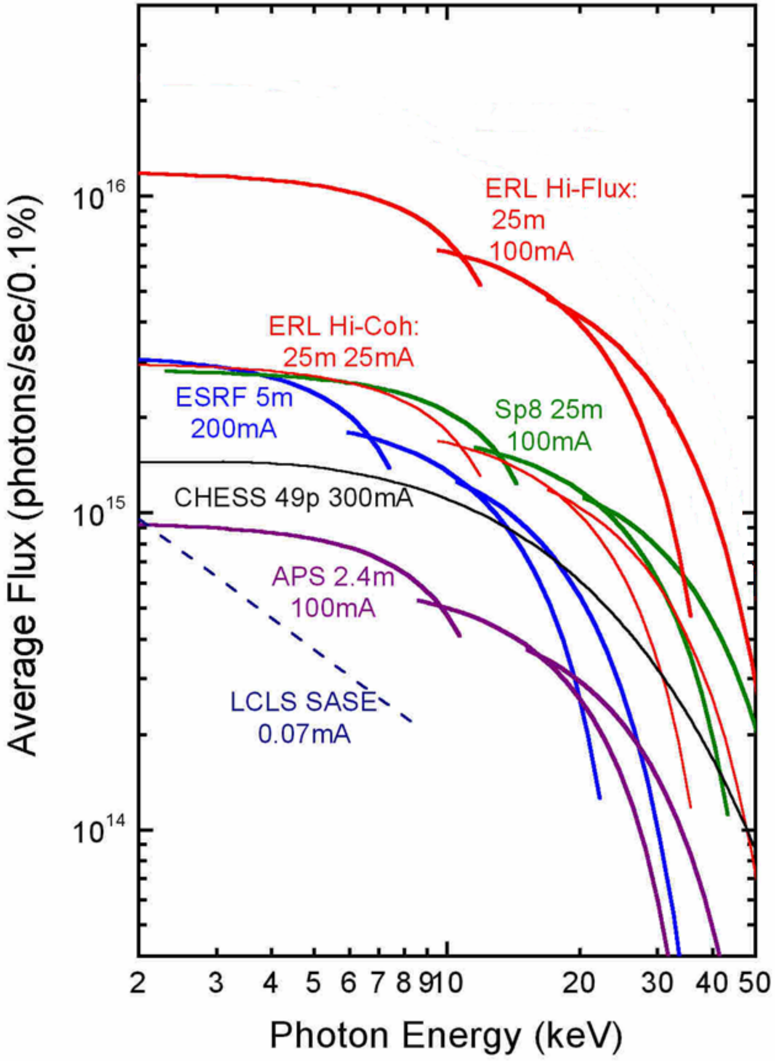
- **Many experiments are x-ray photon starved:**
  - **inelastic x-ray scattering**
  - **powder diffraction from phase transitions**
  - **in diamond anvil cells, etc.**
- **Solution is many periods on the undulator (i.e. long IDs, go to short periods and narrow gaps), superconducting helical und.**
- **This may create heating problem on the crystal optics – so going without a monochromator may be feasible given enough periods (~ 1000 periods).**
- **We plan several 25 m long IDs for these purposes.**



Hi-coherence opportunity

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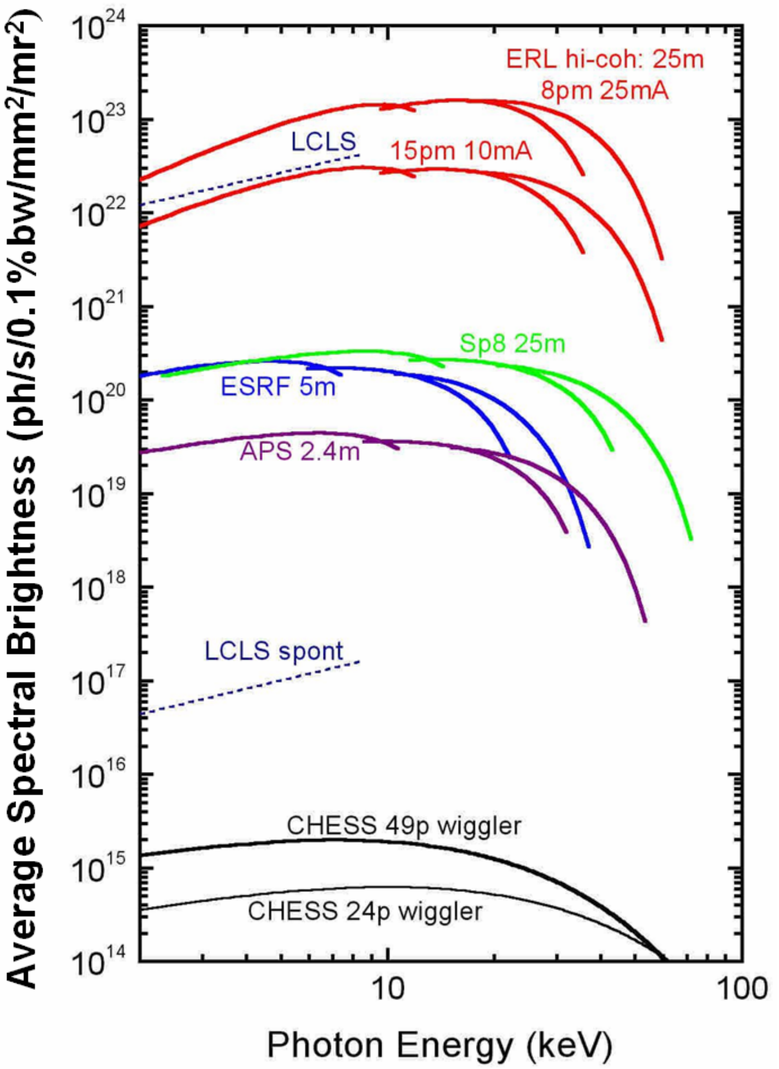
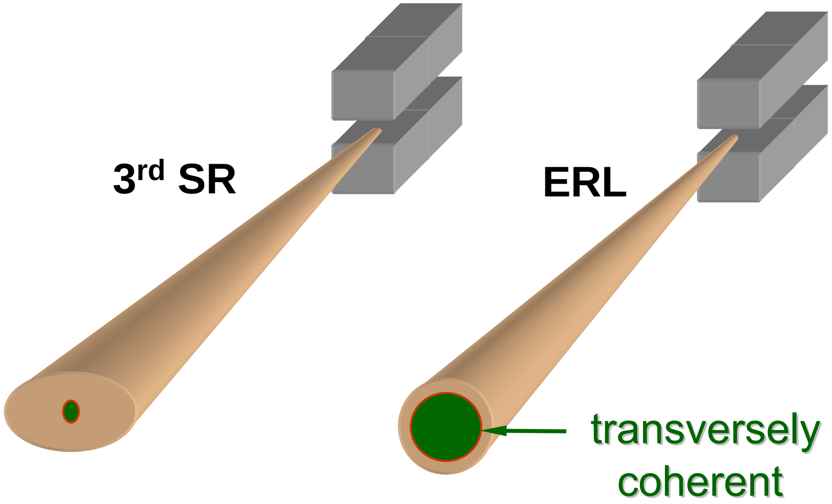
- **Run the ERL to maximize spectral brightness – good for coherence applications**
- **Make a few micron diameter electron source size – good for possibly making a one nm diameter hard x-ray beam**

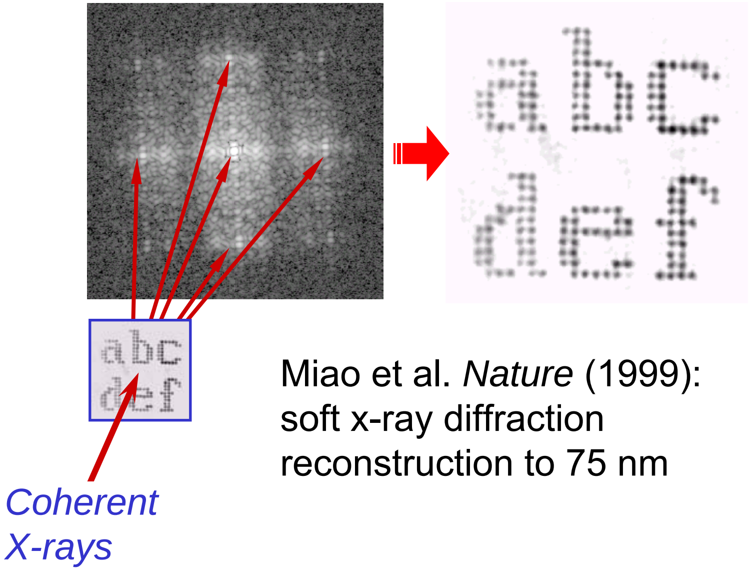


Molecular Imaging

- Molecular imaging requires much higher lateral resolution => limit on optics
- To go beyond the limit, lens less diffraction imaging using a transversely coherent beam is an attractive alternative
- Coherent diffraction imaging is similar to crystallography, but for noncrystalline materials

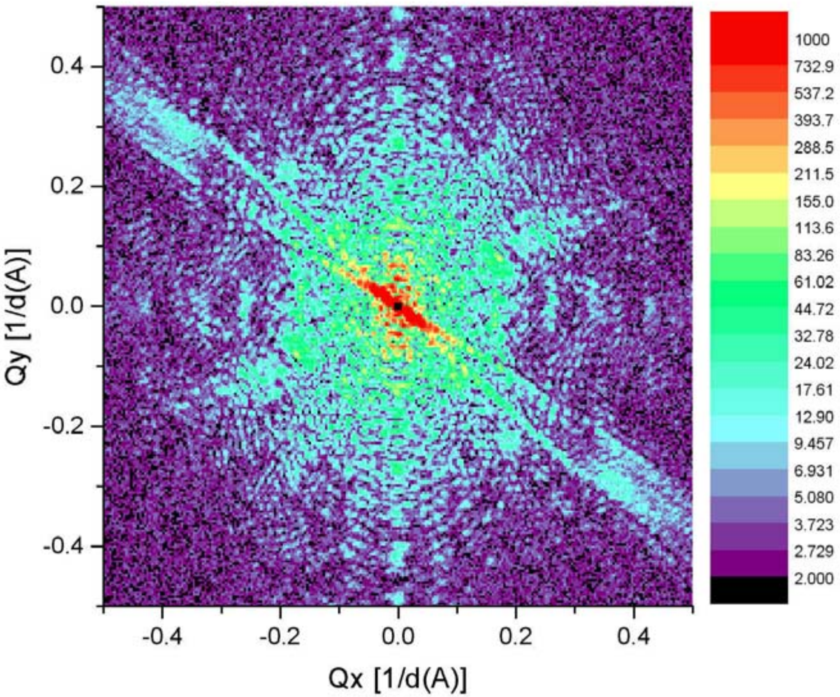


- Present Status: using a pin-hole to select a coherent x-ray beam
- Future ERL sources would change this dramatically:
  - ➔ almost fully coherent x-ray beams
  - ➔ 3,000 fold increase in coherent flux
- Open up structural science to noncrystalline materials



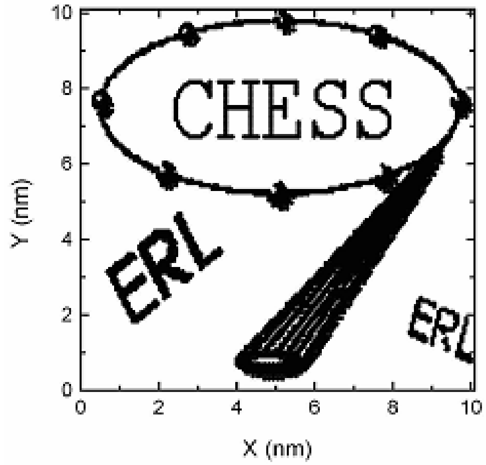
Miao et al. *Nature* (1999): soft x-ray diffraction reconstruction to 75 nm

Simulated Coherent Diffraction Data



← Shen, Bazarov & Thibault., Cover image of Journal of Synchrotron Radiation **11**, 371 (2004) from about 3,000 gold atoms on a 10 nm x 10 nm square

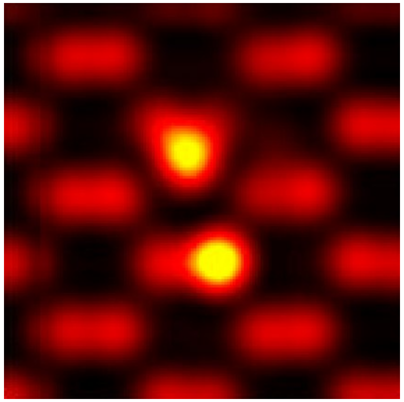
Phase retrieval by iterative methods developed by V. Elser's group →



Conclusion: Image resolution (including effects of radiation damage) with ERL is estimate to be of order 5-10 nm for biological objects, and better than 1 nm for materials samples

Atom-sized X-ray Beam Applications

Microelectronics application:
Debug transistors and IC at the smallest line widths where increasingly high-dopant density favors formation of electrically inactive clusters (a problem!)



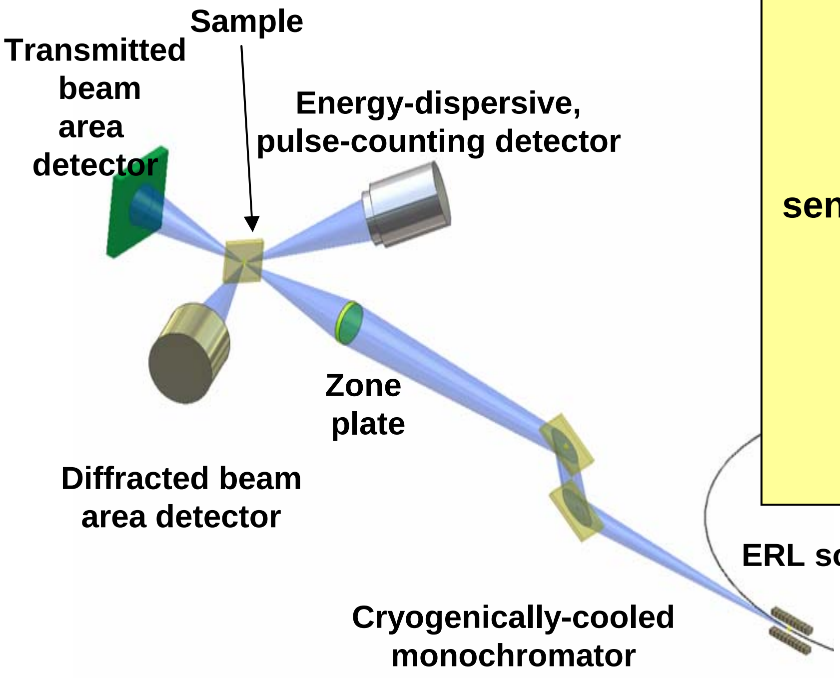
- Two Sb atoms in cluster(yellow) in 20 Angstrom thin Si wafer,
- TEM imaging with 200 keV electrons
- **from Paul Voyles (Bell Laboratories, Lucent), et al. Nature, 416 (2002) 826-828.**

Conclusion: The ERL, for the first time, will make it possible to do x-ray experiments on a single atom, in-situ in thick samples with buried environments, etc.
Thus we will be able to make scanning fluorescent image maps,
near edge and XAFS scans to determine the near neighbor environment,
fluorescent tomography, holography, etc.

ERL Provides Unprecedented Nanobeams for X-ray Experiments

Storage ring nanobeam flux limited by source size, shape, and divergence.

- **Intense 1-10 nm probe size (rms), 1-10 keV beam allows study of nanostructures and molecules**
- **Quantitative atomic-scale structure, strain, orientation imaging**
- **Increase fluorescent trace element sensitivity from present 10^{-19} g to single atom (10^{-24} g)**
- **Sensitive to chemical state via XAFS at at ultra-low concentrations**
- **Ability to penetrate thick layers, nasty gas environments, etc. (as opposed to EM)**



ERL source with electron beam size of 2 microns rms for 1 m long undulator and 0.5 m beta function demagnify by 2000x to make 1 nm beam size, etc.

Biological and Polymer Science:

Structural dynamics of macromolecular solutions

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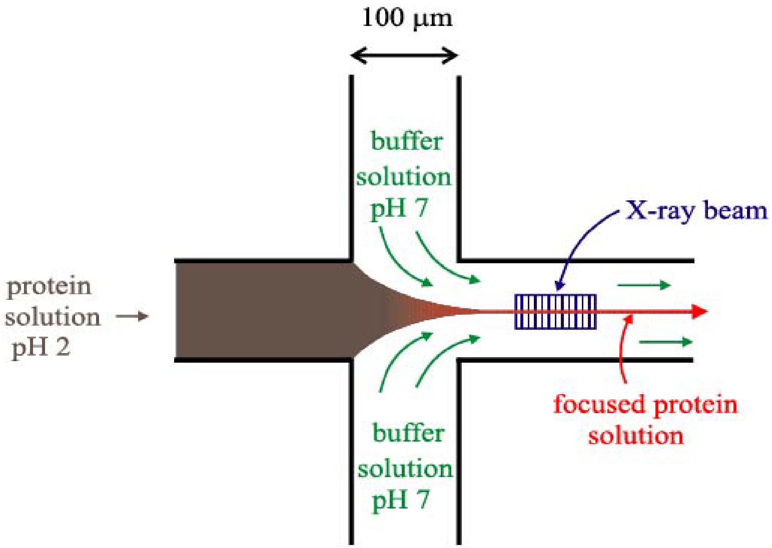
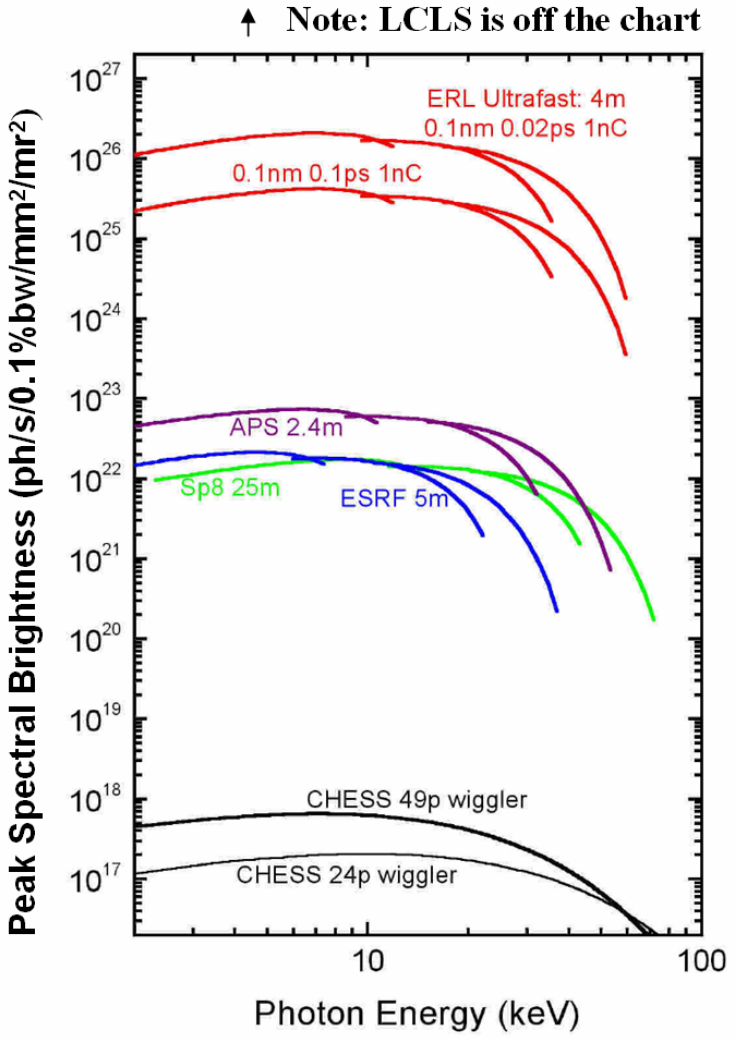
- Examples: folding/unfolding of proteins & RNA; assembly of fibers; polymer collapse upon solvent changes; conformational changes upon ligand binding; monomer/multimer association.
- Microfabricated laminar flow cells access microsecond equilibration mixing times.
- Data acquisition entirely limited by source brilliance. The ERL will extend time scales from present milliseconds to microseconds.



Ultra-fast opportunity

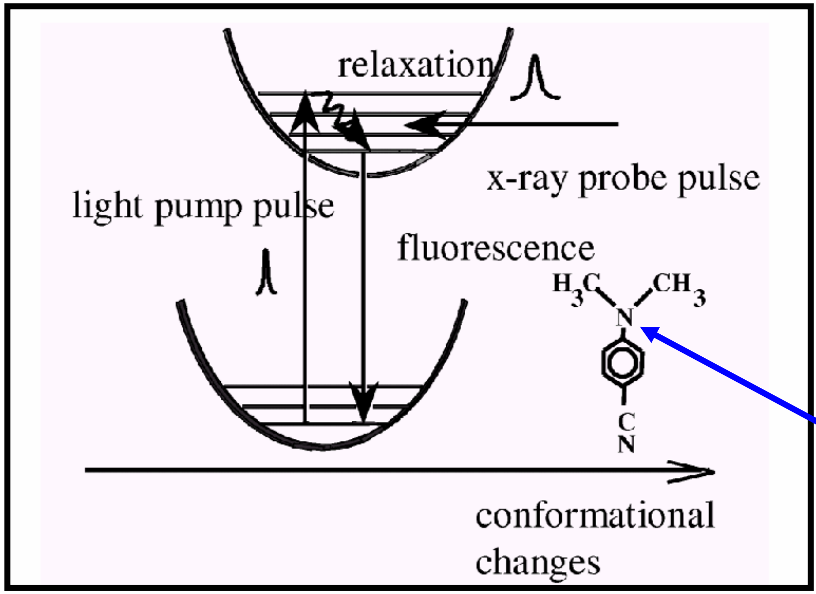
- **Run the ERL to minimize the pulse duration**
- **Go to 1 nC per pulse, work between bunch compressors, squeeze 2 psec down to 50 fs regime (20 fs longer term goal)**
- **Find stroboscopic experiments that can make use a 1 MHz or faster repetition rate.**
- **Powder diffraction of M. Wullf**
- **Exafs of hydration from R. Falcone & Schoenlein**
- **Resonant sliding charge density waves from J. Brock**

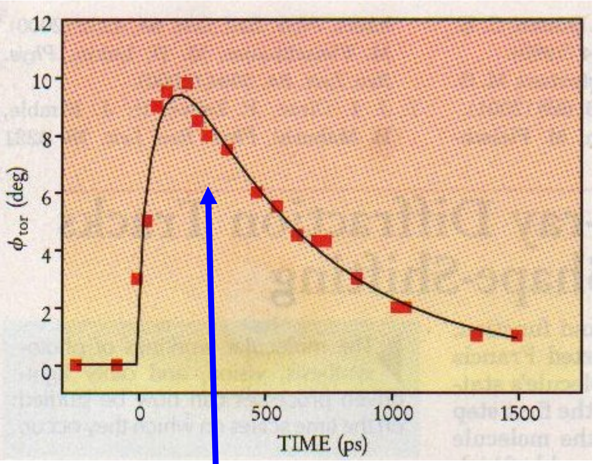

↑ Note: LCLS is off the chart

ERL Enables Following Structure of Ultrafast Chemical Reactions

Scientific challenge is to understand the structural evolution of the "transition state(s)" intermediate between reactant and product species.

S. Techert, F. Schotte, and M. Wulff, Phys. Rev. Lett. **86**, 2030-2033 (2001).

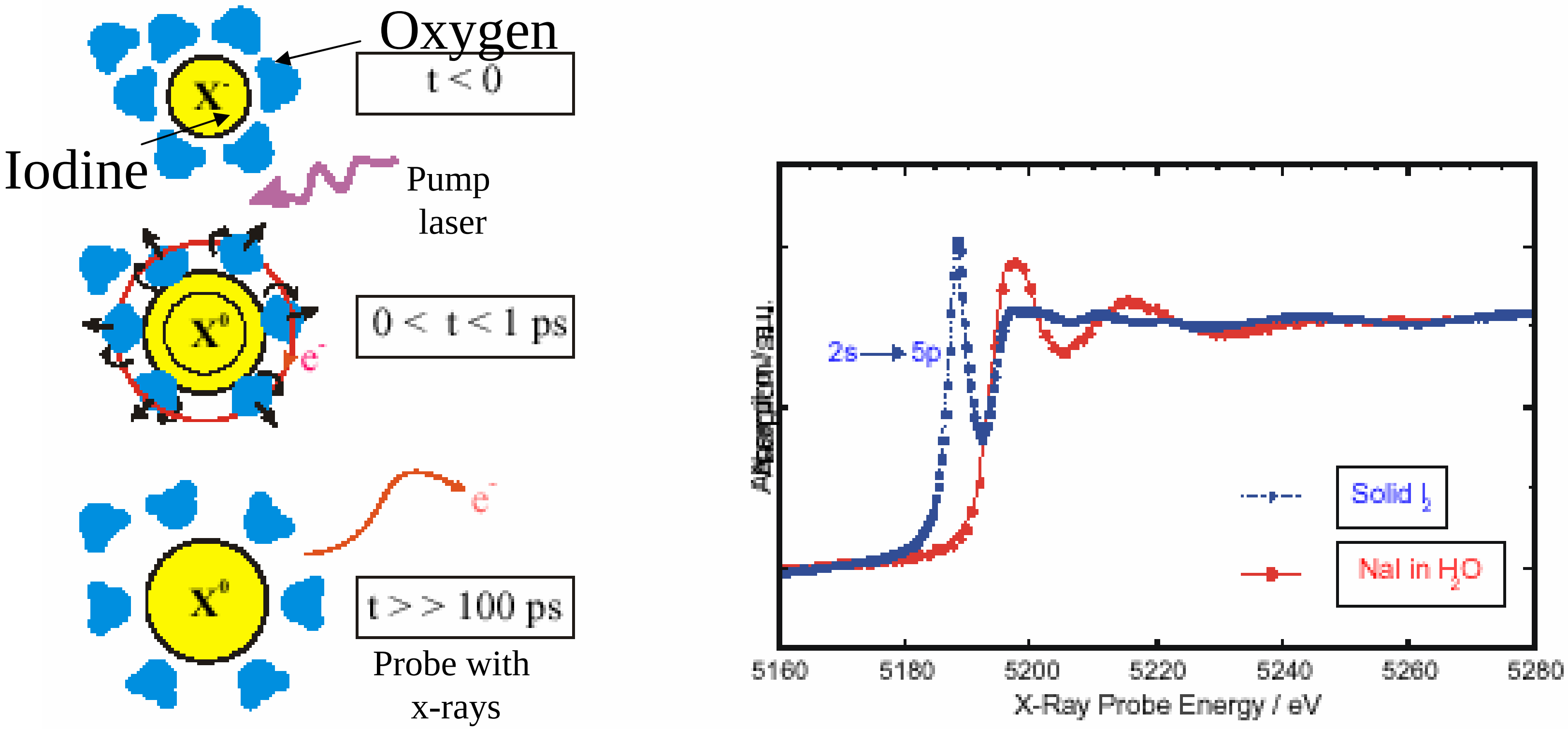




ESRF expt. showed 10° of bond rotation over 100's of picoseconds

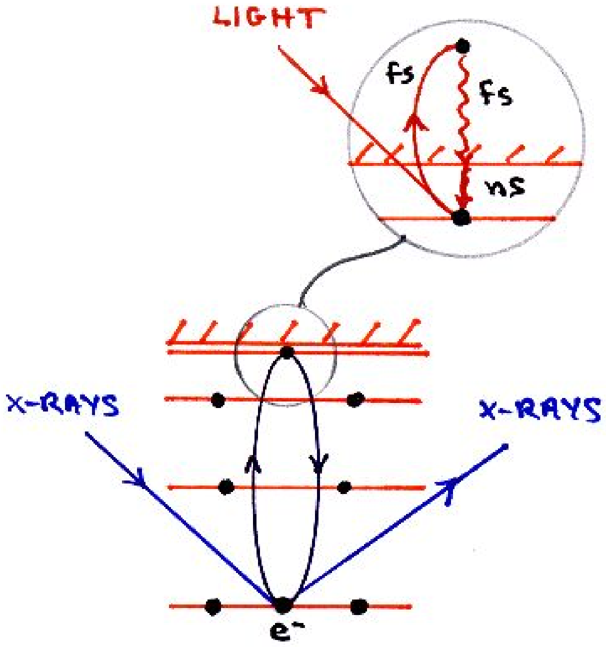
ERL can follow reactions on the 100's of femtosecond time scale.

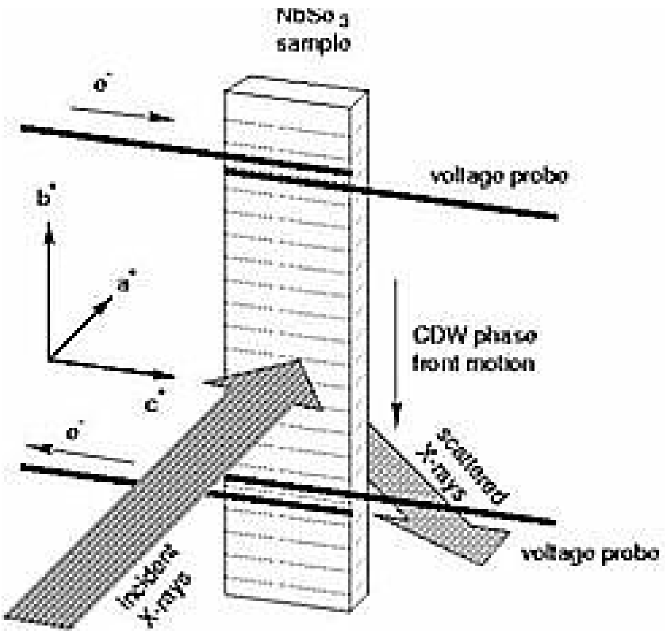
Dynamics of Hydration Are Not Well Understood



Schematic illustration of Photo-neutralization of I- in liquid phase. EXAFS of 2*s* → 5*p*. Change in spectra arises from changed I-O distances. (From Schoenlein & Falcone). ERL would allow examination of intermediate states and to develop structural models of what really happens during hydration!

Ultra-fast Dynamics of Charge Density Waves





Mode-locked Ti:Al_2O_3 Laser, 78 MHz repetition rate, 50-70 fs pulse width

$\lambda \approx 800$ nm (1.58 eV), 100 µm spot, 0.1 – 1 µJ/cm^2

Joel Brock, Applied Physics, Cornell Univ.

Technical challenges

Short period, short gap, but long undulators with phased segments
X-ray windows that preserve coherence
X-ray BPMs that work on a submicron scale
X-ray monochromators that don’t distort under a high-heat load
X-ray optics to make a one nm diameter hard x-ray beam
X-ray mirrors with less than 0.01 micro radian slope error, roughness of ~0.01 Angstrom
Specialized pixel array area x-ray detectors with nsec readout time

In some cases, 3rd generation quality instrumentation is sufficient. In other cases, Important specs have to be tightened up by factors of 10 to 100 to fully use an ERL quality beam.

Conclusions

- Improved ERL machine properties leads to new scientific capabilities
- Virtually all the supporting hardware will need upgrading (optics, windows, detectors, etc.) to match the ERL challenges
- [Some equally challenging opportunities will arise as storage rings and XFELs continue in development as well.]
- This phase of development may push to the fundamental limits on materials, optics, mechanics, electronics, nanofabrication, etc. & should be a great time for scientists & engineers!

Last slide

The End

High Pressure: Materials, Engineering, Geological and Space Sciences.

J. B. Parise, H.- K. Mao, and R. Hemley at ERL Workshop (2000)

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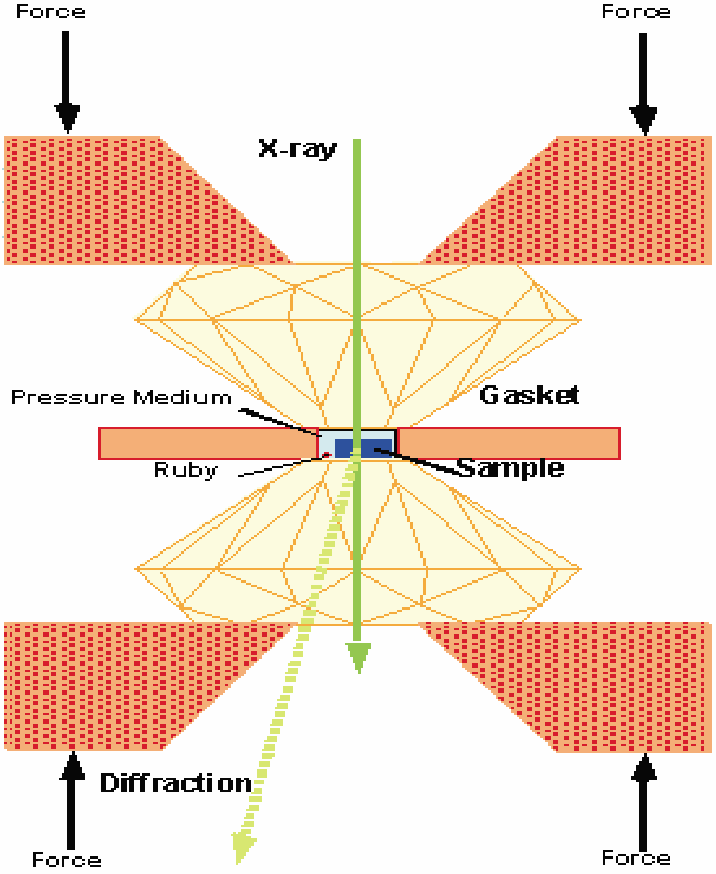
- HP experiments are brightness-limited. Time resolved experiments for plasticity, rheology measurements, phase transitions, etc. are especially photon starved.
- Higher P ⇒ smaller samples.
- No ideal pressurization medium ⇒ need to scan sample.
- Peak-to-background critical.
- ERL will greatly extend pressures and samples that can be studied.



Parise, Hemley & Mao

High Pressure Science Areas Expanded by ERL

- **Nature of dense hydrogen -** *From cryogenic to brown dwarf conditions*
- **Composition, elasticity, and thermal state of Earth’s core -** *Complex alloys to core P- T*
- **Structures of complex hydrous phases -** *Clathrates, molecular compounds, hydrous silicates*
- **Supercritical fluids and liquids -** *Structure and dynamics and effect on chemical reactions*
- **Structure & dynamics of silicate melts & glasses -** *Implications for glass technology & volcanism*
- **Planetary ices -** *Structure, strength, and dynamics of ices under P, T, and stress*
- **Real- time in situ monitoring of transformations in ‘real rocks” -** *Modeling subduction to high P- T conditions*
- **Strength and rheology of materials, including Earth materials -** *Relationship to brittle and ductile failure*
- **Influence of pressure and stress on magnetic properties -** *From low to high temperatures*
- **Dynamics of protein folding and unfolding -** *Implications for food technology and life at extreme conditions*
- **Structure and dynamics of nanomaterials under pressure -** *Nanotubes, fullerenes, and their derivatives*
- **General phase transition studies -** *Mechanisms and identification with unprecedented resolution*
- **Stockpile stewardship issues -** *Light element studies for code verification*

From, John Parise, SUNY Stonybrook, at ERL Science Workshop in 2000