ERL Based Synchrotron Radiation Light Sources

Charles K. Sinclair
Wilson Laboratory
Cornell University

The Motivation for an ERL Light Source – X-ray Experimenters Needs

- Higher brilliance – allows one to work with smaller samples
- Higher coherent flux – allows one to capitalize on interference effects
- Shorter duration pulses – allows one to conduct pump-probe experiments

These needs translate into a requirement for high average current electron beams with much smaller emittances and much shorter bunch lengths

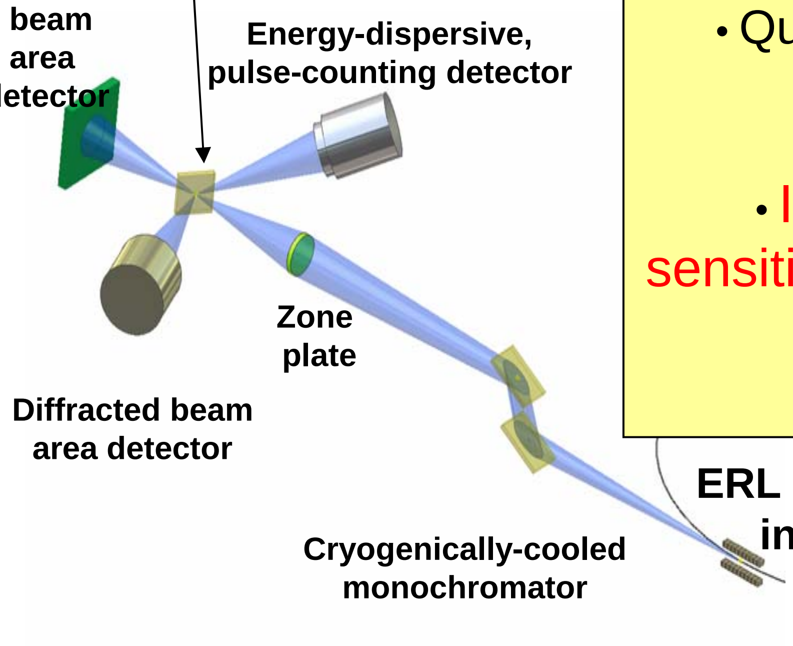
X-ray beam characteristics depend on electron beam properties

- Flux ~ I (average current)
- Brilliance ~ $I/\varepsilon_x\varepsilon_y$ (ε_x and ε_y are emittances)
- Peak Brilliance ~ $I/\varepsilon_x\varepsilon_y\tau$ (τ is bunch length)
- Coherent Flux ~ $I/\varepsilon_x\varepsilon_y$
- Photon Degeneracy ~ $I/\varepsilon_x\varepsilon_y\tau$

I, ε_x, ε_y, and τ are the electron beam properties that determine the key X-ray beam qualities.

ERL Will Provide Unprecedented Nanobeams

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

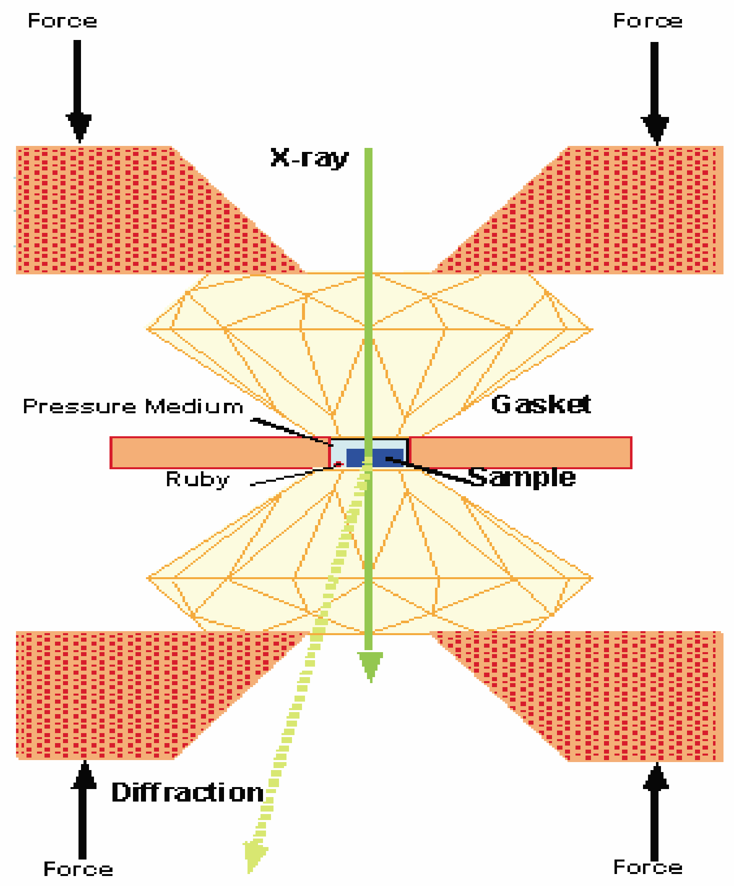


- Intense 1-10 nm probe size (rms), 1-10 keV beam allows study of nanostructures and molecules
- Quantitative atomic-scale structure, strain, orientation imaging
- Increase fluorescent trace element sensitivity from present 10^{-19} g to single atom (10^{-24} g)

ERL source with 2 micron rms electron beam size in a 1 m long undulator with a 0.5 m beta function. Demagnify by 2000x to make a 1 nm beam size.

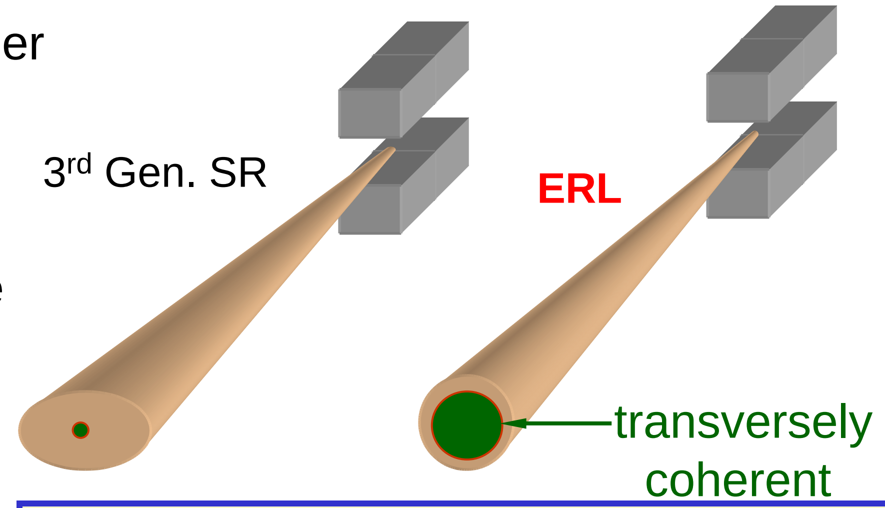
High Pressure: Materials, Engineering, Geological and Space Sciences

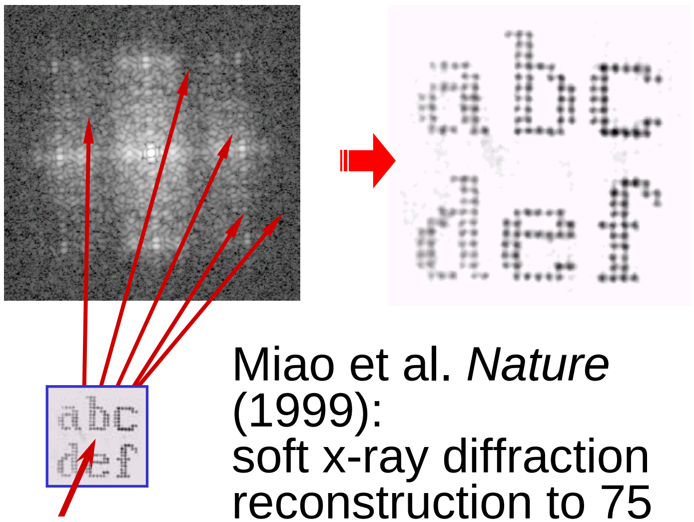
- High Pressure experiments are brightness-limited. Time resolved experiments for plasticity, rheology measurements, phase transitions, etc. are especially photon starved.
- Higher P $\Rightarrow$ smaller samples.
- The high brightness of ERL x-ray beams will greatly extend the pressures and samples that can be studied.



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



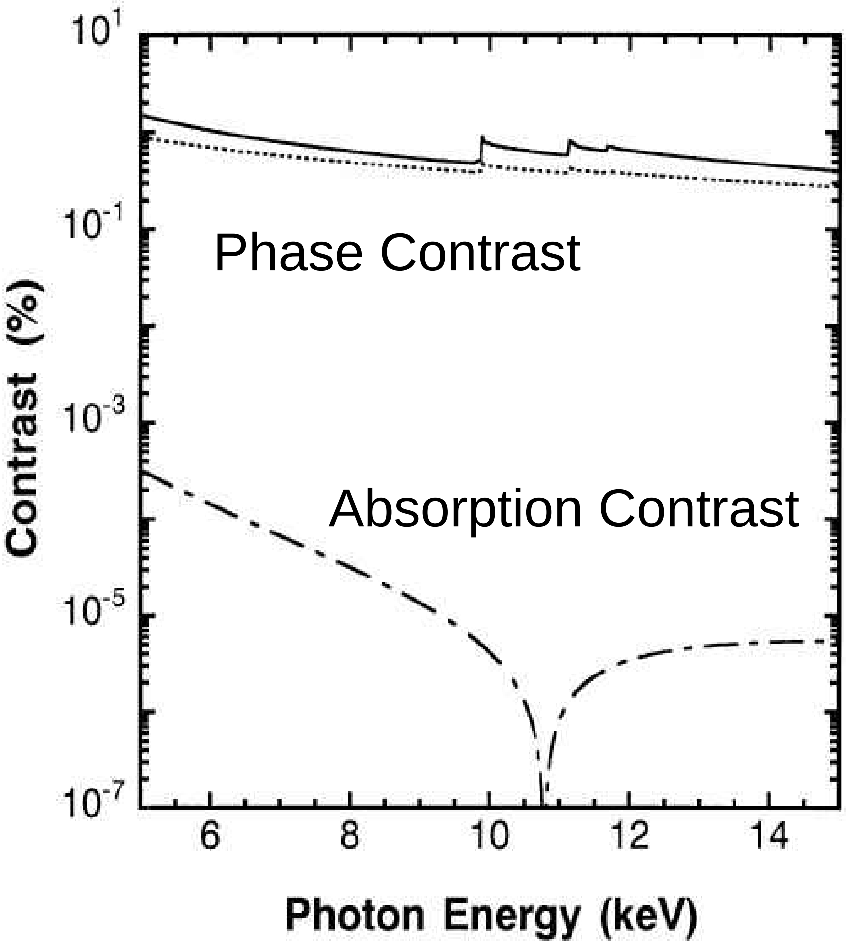


Coherent X-rays

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

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

Phase vs. Absorption Contrast

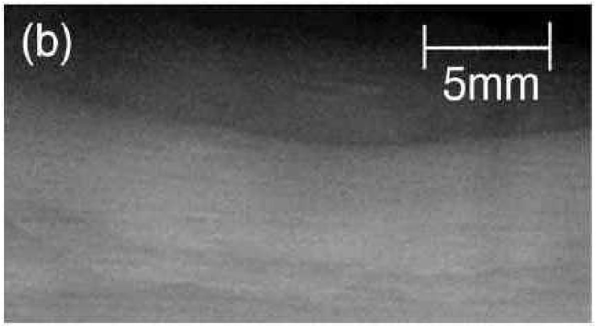


Kagoshima et al. (2001)

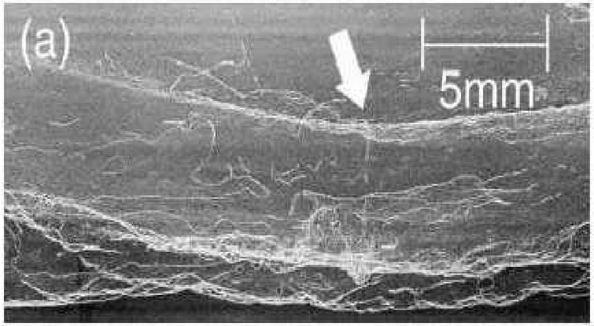
Protein $C_{94}H_{139}N_{24}O_{31}S$ in water

Phase contrast is 10^4 higher than absorption contrast for protein in water at 8 keV

Absorption contrast ~ λ^3



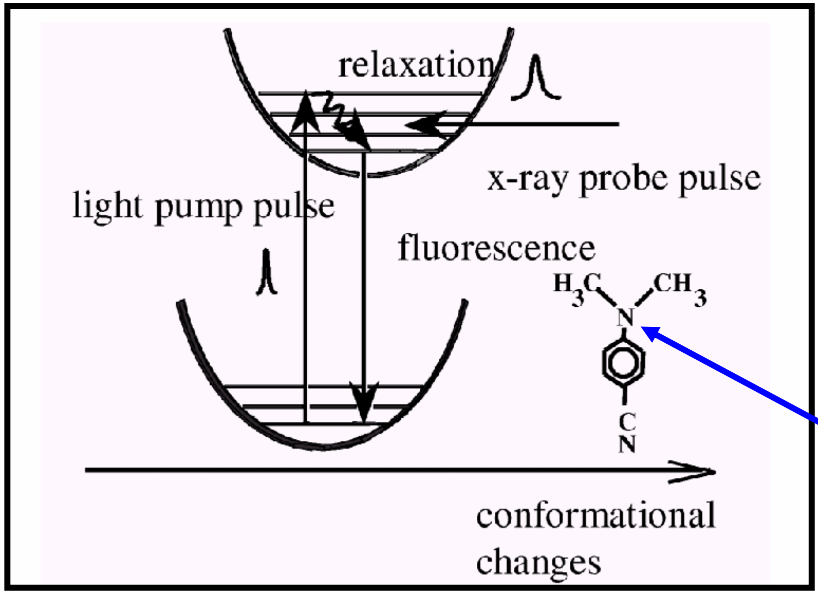
Phase contrast ~ λ

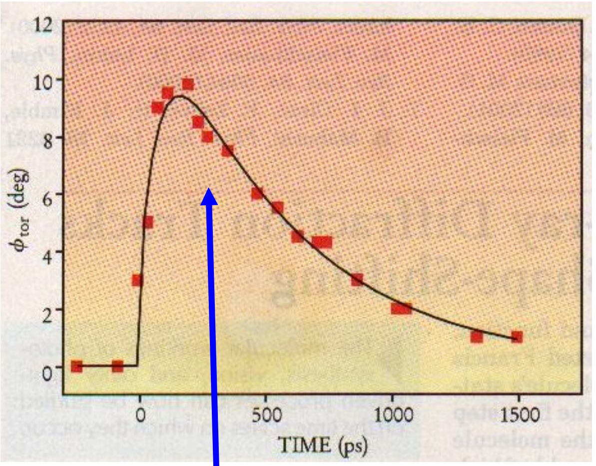


ERL Enables Following the Structure of Ultrafast Chemical Reactions

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).

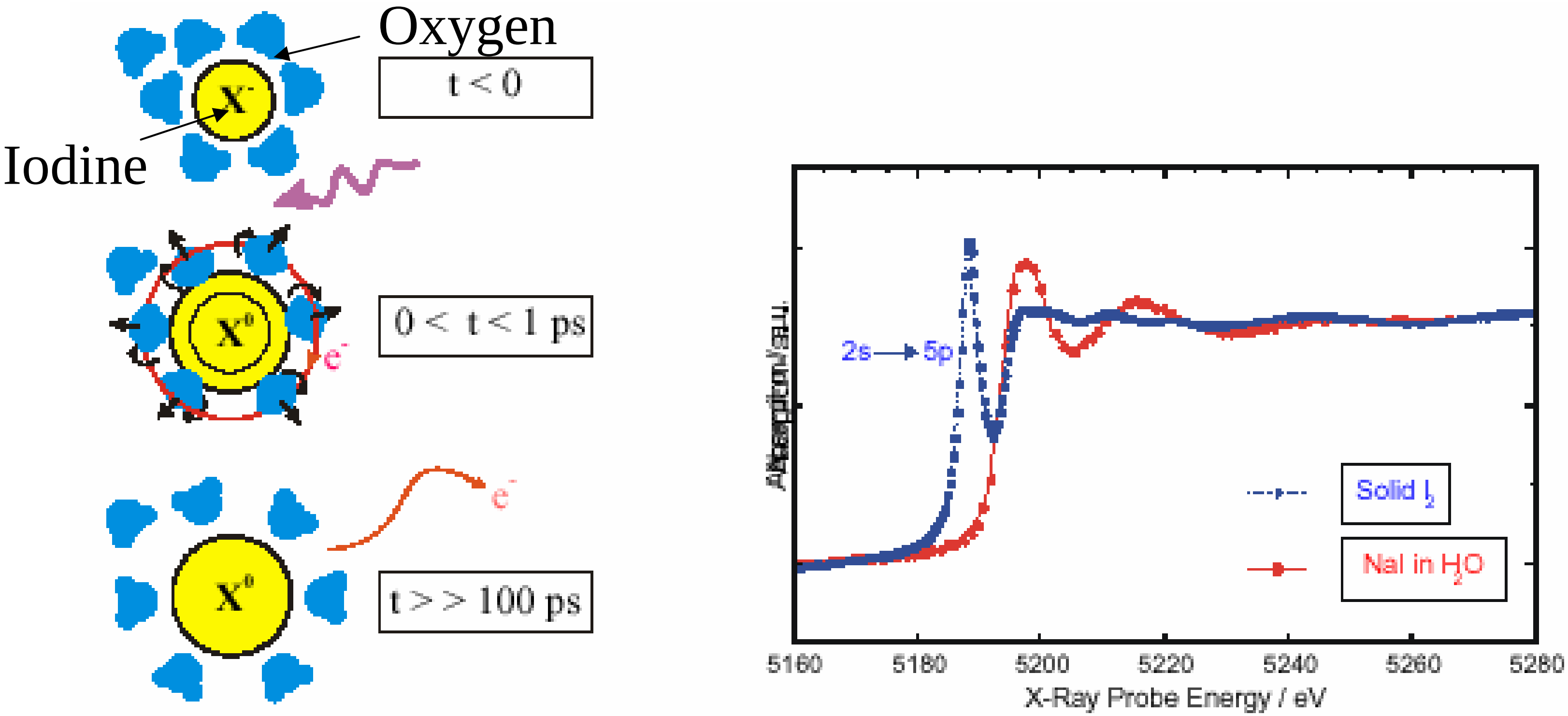




ESRF expt. showed 10° of bond rotation over 100's of picoseconds

An ERL allows following reactions on the 100's of femtosecond time scale.

Dynamics of Hydration Are Not Well Understood



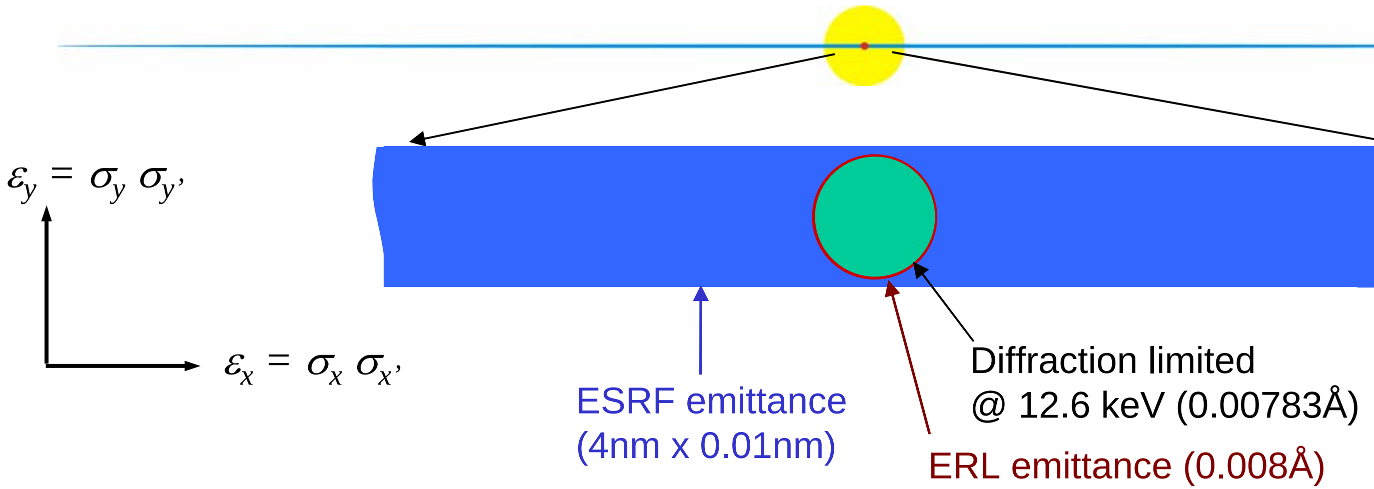
Schematic illustration of Photo-neutralization of I- in liquid phase. EXAFS of 2*s* → 5*p*. Change in spectra arises from changed I-O distances. (From Schoenlein & Falcone).

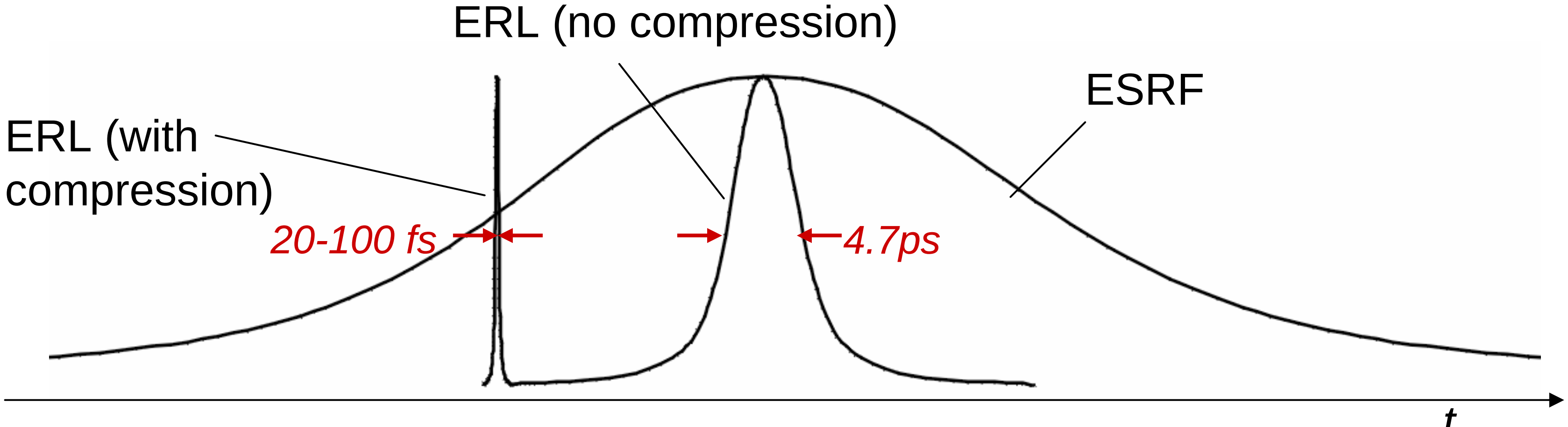
An ERL will allow examination of intermediate states and the development of structural models of what really happens during hydration!

Comparison – APS and ERL

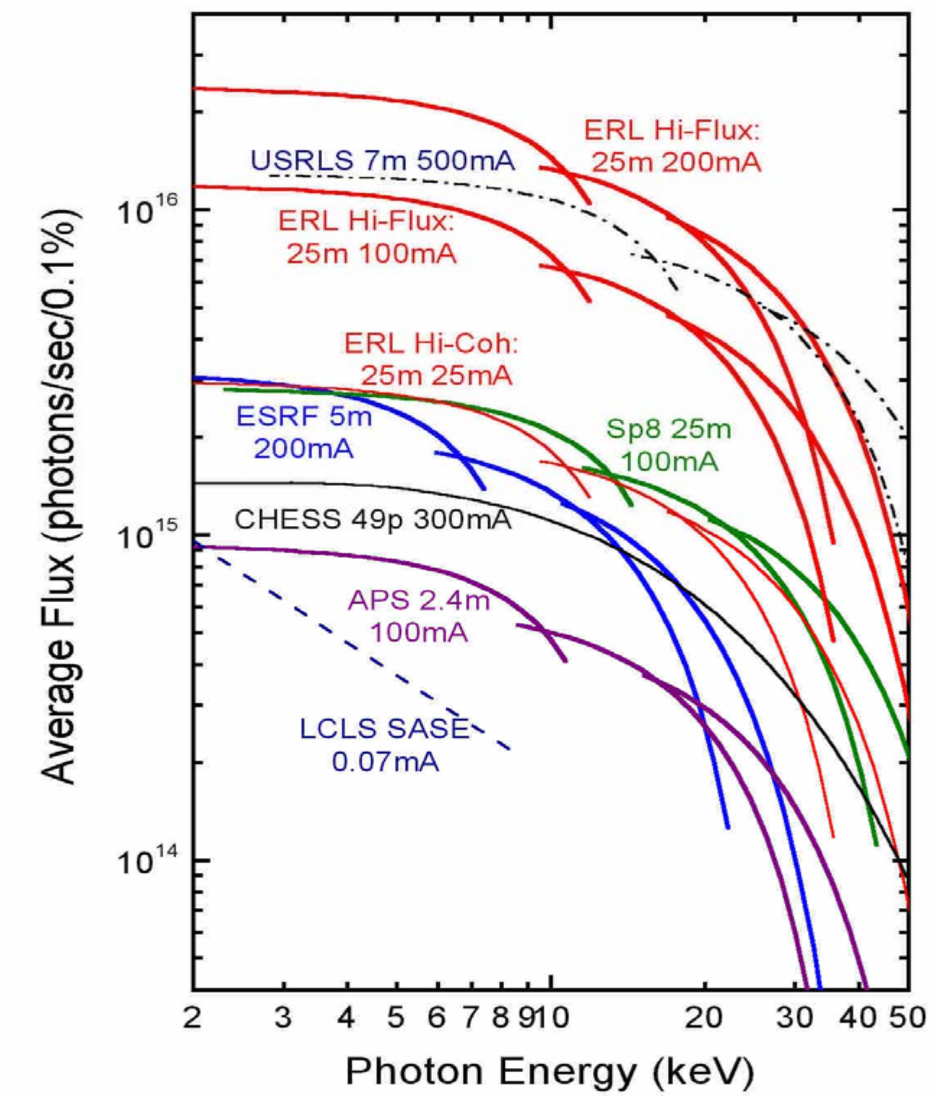
Parameter	APS 3rd generation storage ring	Energy recovery linac	Gain with ERL
Electron source size in microns (rms)	239(h) x 15(v)	2(h) x 2(v)	1/900 in area
Micro x-ray beam size	100 nm to 1 micron	1 nm	100 to 1000
Coherent flux x-rays/sec/0.1% bw	3×10^{11}	9×10^{15}	3000
Pulse duration (rms)	32 ps	<100 fs	> 320 times shorter

Comparison – ESRF and Hypothetical ERL

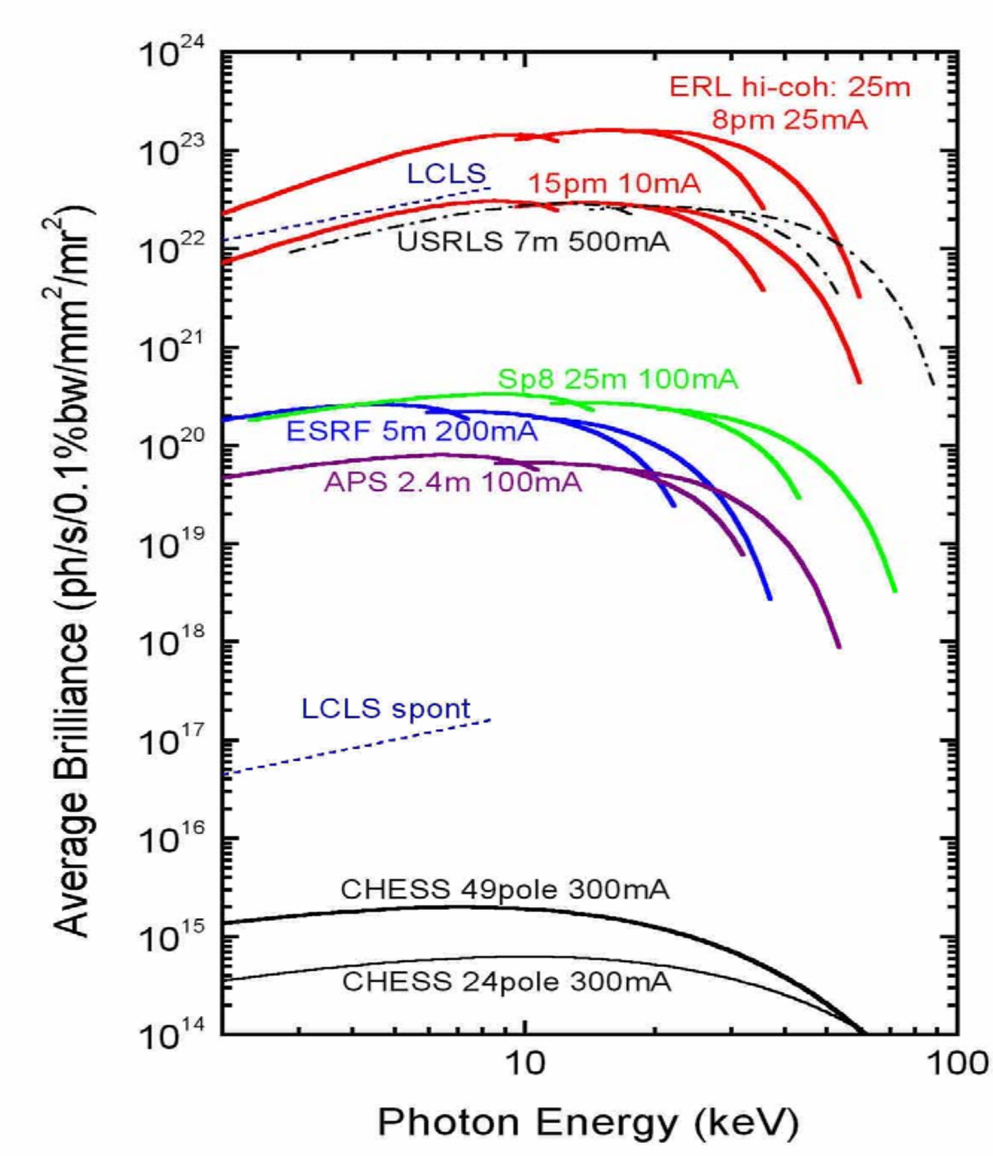




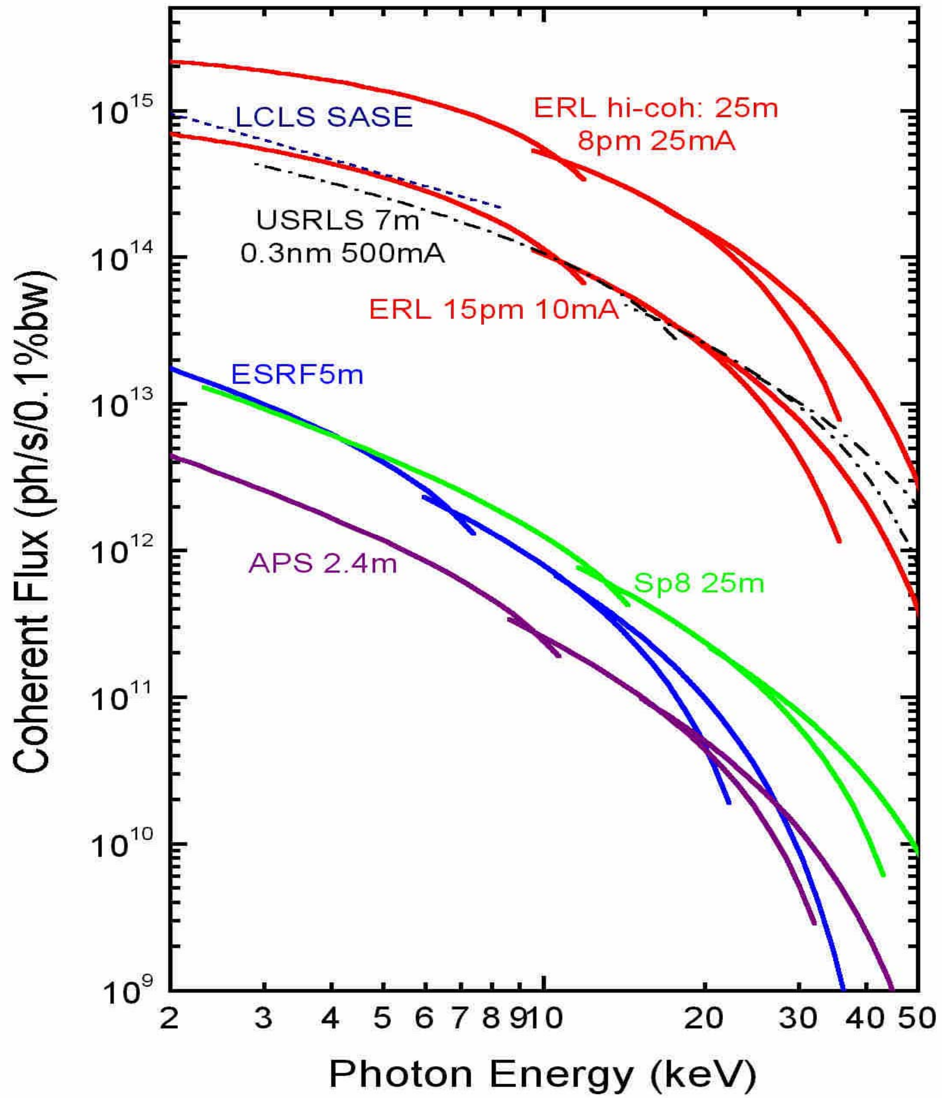
5 GeV ERL – Average Flux



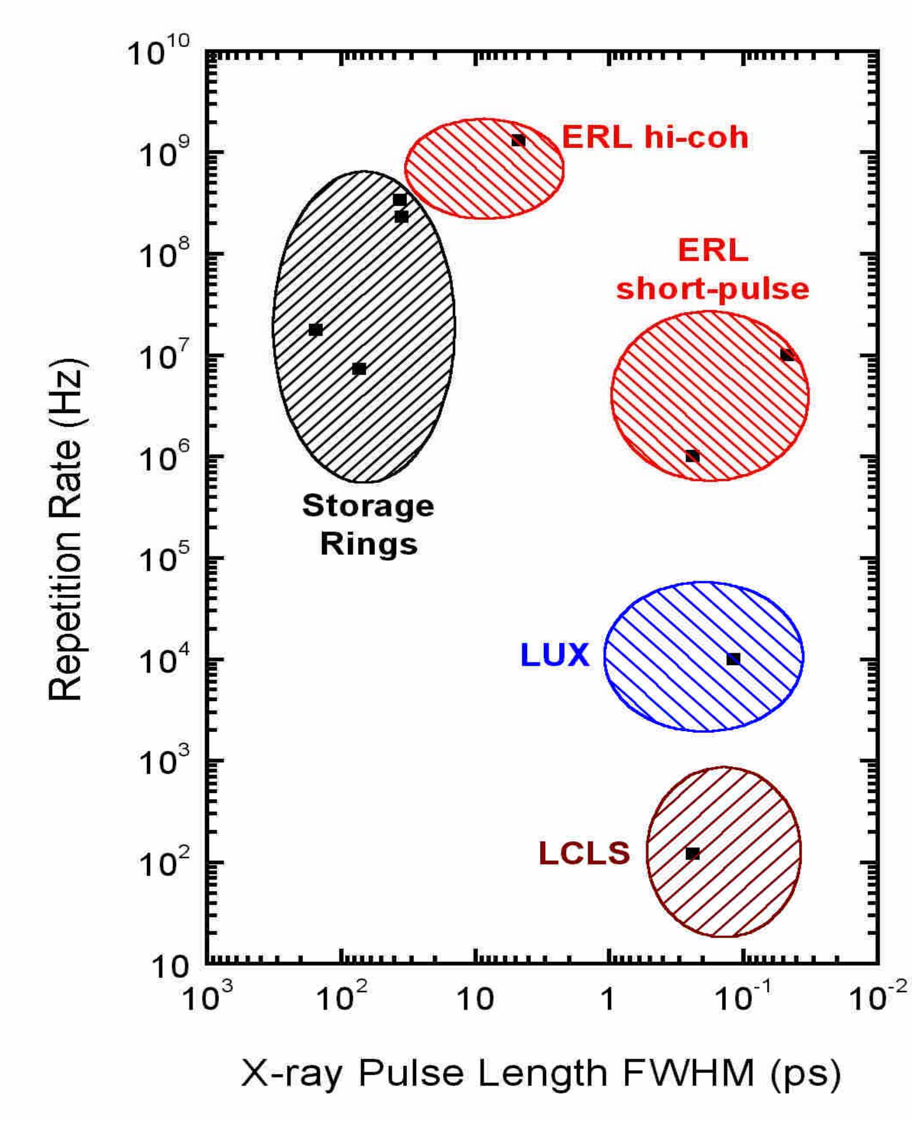
5 GeV ERL – Average Brilliance



5 GeV ERL – Coherent Flux



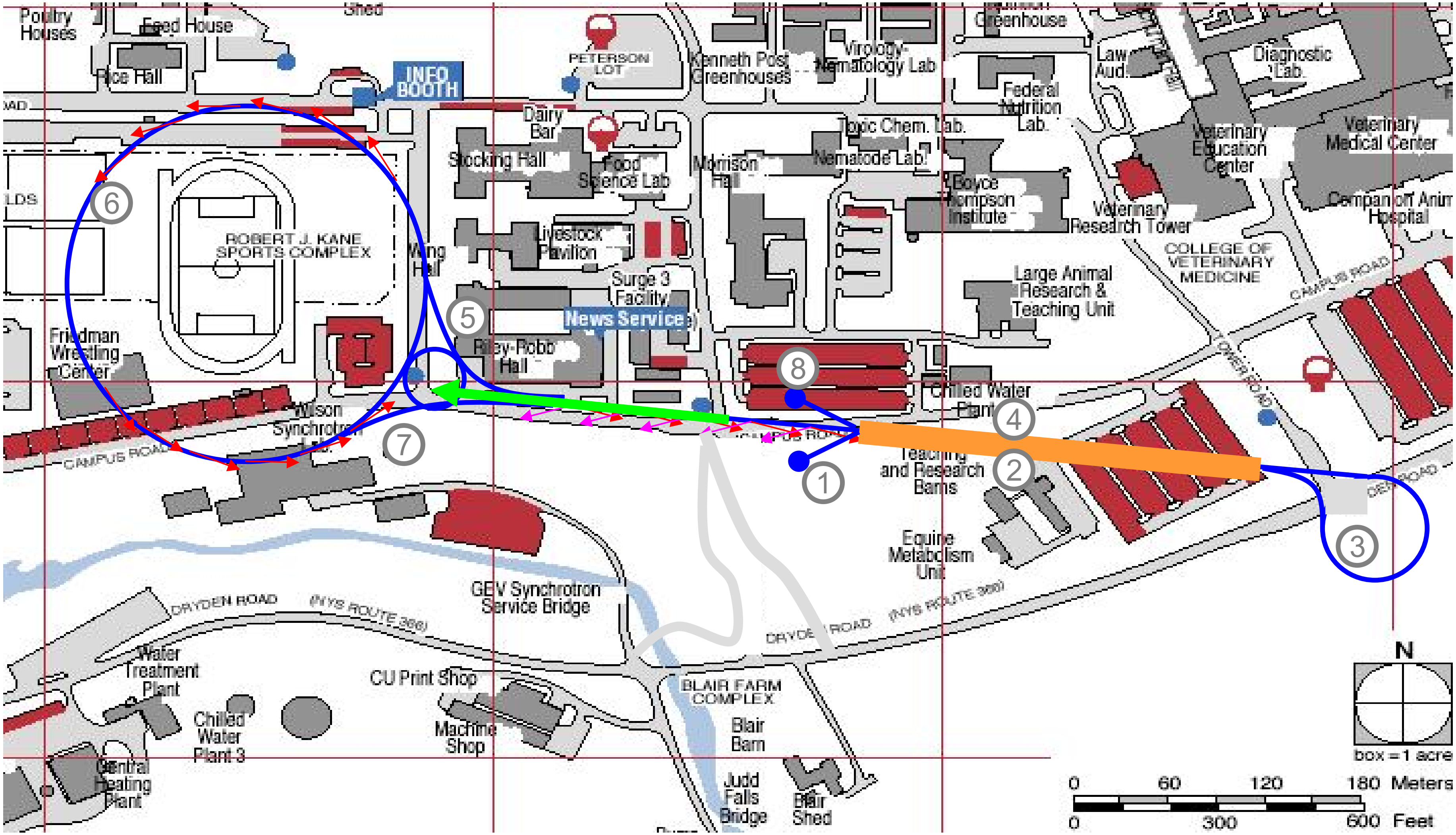
Short Pulses at High Rep Rate



ERLs are an upgrade path for any existing Storage Ring

- To utilize the beam qualities of an ERL X-ray source, X-ray optics and insertion device technology must also be improved
- The generally lower $\Delta E/E$ delivered by an ERL allows the use of longer undulators
- Beam stability commensurate with the low emittance is required
- The X-ray experimental techniques for an ERL are extrapolations from present technologies, rather than completely new

A possible ERL upgrade to CESR



Typical ERL Light Source Parameters

- Beam Energy – 5 GeV
- Fundamental frequency – 1300 MHz
- Average beam current – normal mode – 100 mA (77 pc/bunch)
- Average beam current – short pulse mode - > 1 mA (~ 1 nC/bunch)
- Normalized transverse emittance at full energy – below 2 mm-mrad rms in normal mode
- Bunch length before compression - ~ 2 ps rms
- Bunch length after compression - < 100 fs rms
- Uncompressed $\Delta E/E \sim 2 \times 10^{-4}$ rms

What are the Challenges?

1. Generate a high average current beam with low transverse and longitudinal emittances
   - DC, RF, or SRF electron gun?

     Each has been demonstrated at some level, and all presently fall well short of our ERL requirements
   - Choice of photocathode (NEA, PEA?) and laser

$$i(mA) = \frac{\lambda(nm)}{124} \bullet P_{laser}(W) \bullet QE(\%)$$

   - Emittance dependence on bunch charge, pulse width, gun voltage, and field strength. What are the optimum values?
   - What is the optimum injector energy?
   - Photocathode operational lifetime?

2. Accelerate to high energy and transport through insertion devices without degrading emittances

- are there limits on the ratio between the full and the injected beam energy?
- what beam current limit is set by BBU?
- are multi-pass recirculation schemes viable for some ERLs?
- how do we deal with emittance degradation from CSR, wake fields, and HOMs?
- Understanding CSR. Benchmarking CSR codes?
- what is the optimum bunch length?
- what are emittance requirements in the short pulse mode?
- emittance growth in injector-main linac merger?
- to what extent can we resolve these questions at existing accelerators (e.g. CEBAF, FEL, etc.)?

3. Pulse compression

- what are the shortest practical pulse widths? What are the pulse width limiting phenomena?
- what is emittance requirement for short pulse applications?
- minimize beam quality degradation during short pulse transport
- how many X-ray beamlines need short pulses?
- is short pulse operation a separate mode entirely?

4. Capital and Operating Cost Optimization

- tradeoff between accelerating gradient, heat load, operating temperature, and refrigerator capital and operating costs
- what are the limitations on the maximum CW accelerating gradient due to field emission?
- what is the maximum Q_{ext} that can be reliably controlled as a function of beam current? What is the best choice of RF power source?
- how well can HOM power be extracted from the cryogenic environment?

5. Many other technical issues

- Beam diagnostics – intercepting or non-intercepting? How do we establish the emittances?
- Halo generation
- Beam loss (n.b. – in CEBAF, instances of ~ 200 nA of localized beam loss have opened vacuum leaks at flange pairs)
- Beam dump (size, protection, stress and fatigue issues…)
- Machine protection (a hit by full beam will melt through in ~ 1 μs)

Summary

- High energy ERLs promise to deliver exceptional SR x-ray beams, with transformational improvements in brightness, coherence, and pulse duration
- ERLs are a natural and cost effective upgrade path for existing storage ring light sources
- The electron injector is a key element of an ERL. At Cornell, we recently received NSF funding to build an injector we believe will deliver 100 mA average current with emittances significantly smaller than our original specification (Bazarov paper in WG-1)

- Important experiments are underway on some of the key issues
  - –BBU (JLab-Cornell collaboration at the FEL)
  - –RF Control (Cornell-JLab collaboration at the FEL and the CEBAF accelerator
  - –Full to injected energy ratio at the CEBAF accelerator (JLab)
- In parallel with our injector development work, we plan to develop a full proposal for a 5 GeV ERL upgrade to the CESR storage ring