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1. Cornell High Energy Synchrotron Source (CHESS) Overview

2. Energy Recovery Linac (ERL) Project

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Synchrotron Radiation (SR) at Cornell

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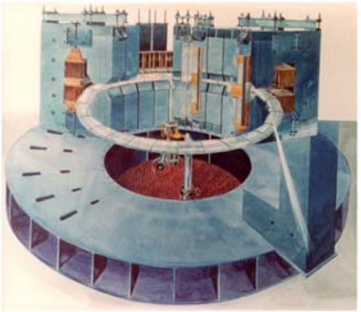
- **SR is an essential tool in national arsenal of analytical capabilities.**
- **Important: 30,000 users, capitalization of $10B - $20B.**

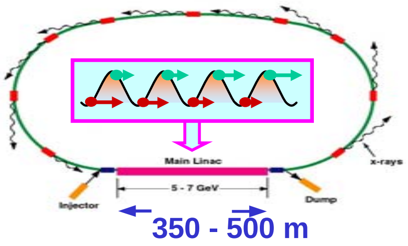
1952 First SR beamline, Newman Lab 300 MeV machine. Hartman, Tomboulian, Corson publish SR studies.



1956 Hartman & Tomboulian, PRL <u>102</u>, 1423.

1979 Cornell Electron Storage Ring (CESR) built and CHESS starts.

2000 ERL work begun.



CHESS Center in a Nutshell

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- 1 of 5 U.S. hard x-ray SR National Facilities, only one on a central university campus.
- Supported by NSF & NIH.
- Full time staff ~60.
- Associated faculty ~12 and their students & post-docs. Distinctive training role for other sources.
- Small. 12 stations.
- Usage: Half physical sci. & eng., Half biological.
- ~1000 user visits/yr. Proposal driven.
- Geographically diverse base of users.
- Extremely productive. ~2 papers/day of beam. Many awards and research accomplishments.
- Deliverables: People, User Science, Technology

Training people is one of our most important contributions to the national effort

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G+B MAGAZINES

SRN

Synchrotron Radiation News

January/February • Vol. 13 No. 1

Focus on Future Visions, Part II

Some Recent User Awards

2003 Nobel Chemistry Prize – Membrane ion channel structure

Rod MacKinnon (Rockefeller Univ.)

2003 Irving Sigal Protein Soc. Young Investigator Award – apoptosis and TGF-ß signaling

Yigong Shi (Princeton Univ.)

2003 Avanti Award in Lipids – Lipid liquid crystals

John Nagle & Stephanie Tristam-Nagle (Carnegie-Mellon Univ.)

2003 Bridgman Award – High pressure physics

Neil Ashcroft (Cornell)

2003 Univ. of Utah Merit of Honor Award – High pressure physics

Arthur Ruoff (Cornell)

2003 Warren Prize – Pair distribution function method to study defects

Takeshi Egami, (Univ. of Pa.)

2003 Compton Award – Resonant magnetic scattering

Martin Blume, Doon Gibbs, Dennis McWhan (BNL) & Kazumichi Namikawa (Tokyo Gakugei Univ.)

2003 Margaret Oakley Dayhoff Award – Protein signaling & cell death

Hao Wu (Cornell Univ., Weill Medical College)

2002 NY Acad. Sciences Mayor’s Young Investigator Award

Hao Wu (Cornell Univ., Weill Medical College)

2002 Linus Pauling ACA Best Student Poster Prize

F.G. Hernandez-Guzman (Hauptmann-Woodward Med. Rsch. Inst.)

2002 DOE Combustion and and Emissions Control R&D Award

Jin Wang, Steve Ciatti, Chris Powell & Yong Yue (Adv. Photon Source, Argonne Lab)

Accelerator Physics, Superconducting & Synchrotron Technology

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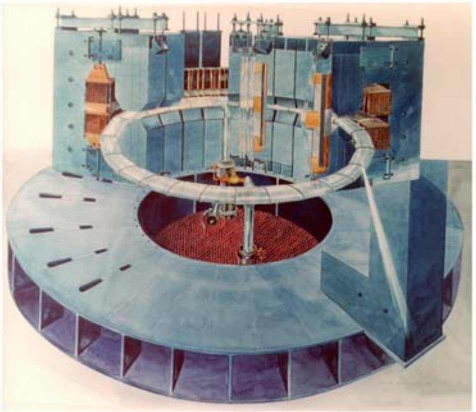
World's first SR beam line, Cornell's 300 MeV Synchrotron. 1952

1945	LNS (LEPP) started by Bethe returning from Los Alamos
1952	World's first SR beamline on 300 MeV synchrotron
1965	Tigner proposes ERL idea
1975	Cornell SC synchrotron tests
1979	Cornell Electron Storage ring (CESR) & CHESS start
1982	First storage ring SC tests
1982	Demonstration of curved crystal sagittal focusing
1984	CEBAF cavities developed & tested at CESR
1985	First mammalian virus structure
1985	Image plate developments
1986	Cryogenic monochromator crystal cooling developed
1987	First hard x-ray circular polarization phase plate
1988	Discovery of resonant x-ray magnetic scattering
1988	Long-period standing waves demonstrated
1989	APS undulator A developed and tested
1989	Development of cryoloop protein crystal freezing
1991	First CCD detectors for protein crystallography
1992	First Complete Stokes Polarimetry for X-rays
1993	First microsecond time resolved XAFS
1995	First TESLA cavity
1998	K^+ Channel structure
1999	First fully SC powered storage ring
2001	First microsecond x-ray Pixel Array Detectors

Key: Red = x-ray; Black = superconducting technology


CESR today

Stations and Techniques

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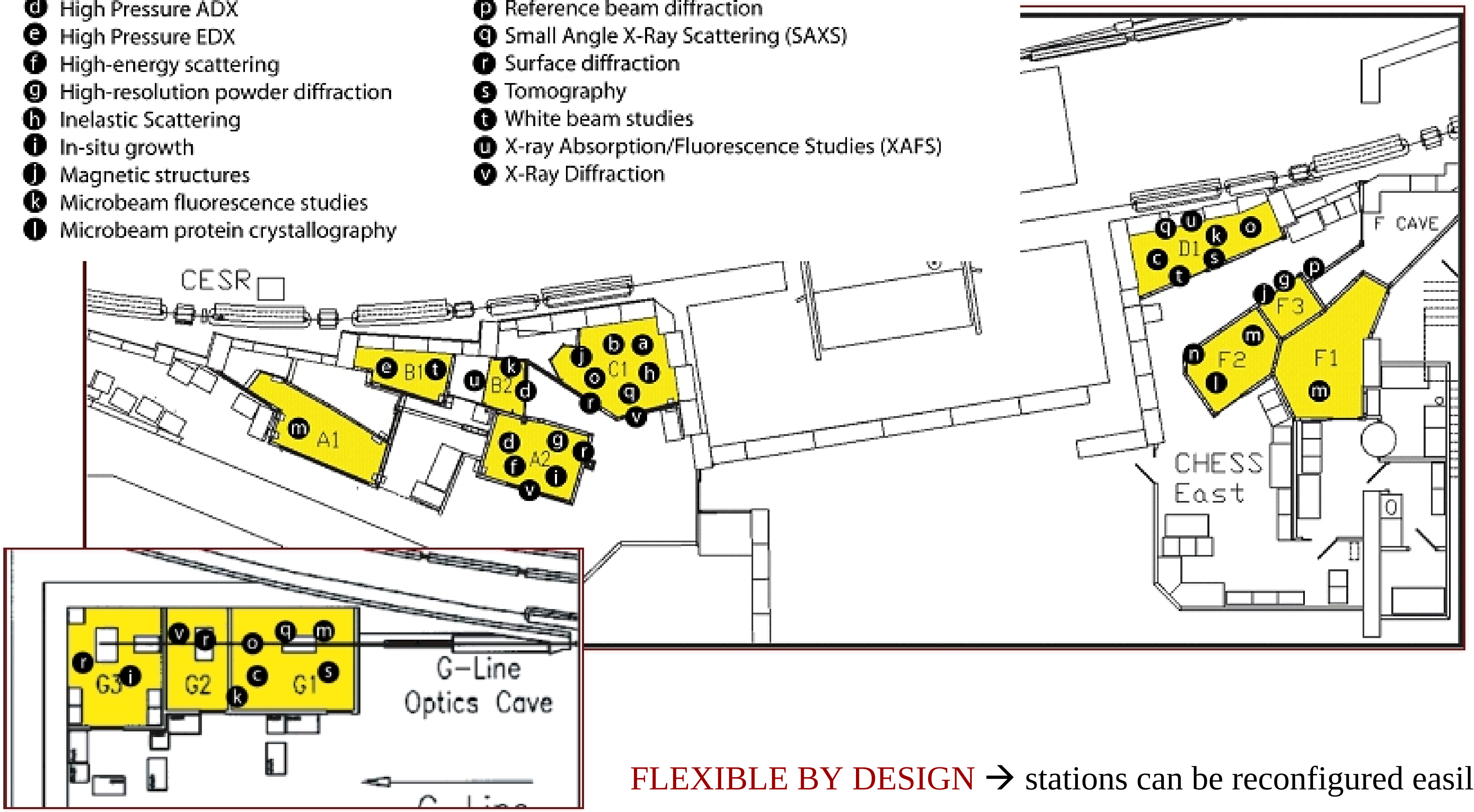
- ⓐ Dual-energy SAXS
- ⓑ Energy Dispersive Optics
- ⓒ Grazing incidence SAXS
- ⓓ High Pressure ADX
- ⓔ High Pressure EDX
- ⓕ High-energy scattering
- ⓖ High-resolution powder diffraction
- ⓗ Inelastic Scattering
- ⓘ In-situ growth
- ⓙ Magnetic structures
- ⓚ Microbeam fluorescence studies
- ⓛ Microbeam protein crystallography
- ⓜ Monochromatic Oscillation Camera Crystallography
- ⓝ Multi-wavelength Anomalous Diffraction
- ⓞ Radiography
- ⓟ Reference beam diffraction
- ⓠ Small Angle X-Ray Scattering (SAXS)
- ⓡ Surface diffraction
- ⓢ Tomography
- ⓣ White beam studies
- ⓤ X-ray Absorption/Fluorescence Studies (XAFS)
- ⓥ X-Ray Diffraction



FLEXIBLE BY DESIGN → stations can be reconfigured easily

NO OBSOLESCENCE → adapt to needs and demands

What About the Future?

ERL Concepts
&
Implications for Analytic Capabilities

Growth in Synchrotron Radiation (SR) demand is both in availability and capability

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What is needed for the most advanced analytical challenges for demanding security projects?

1. High brilliance & flux.
2. Fast x-ray pulses.
3. Small x-ray source size (for microbeams.)
4. Upgrade path, for both storage rings & ERLs.

SR properties follow from bunch emittances

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Flux ~ I (current)

Brilliance ~ $I / \varepsilon_x \varepsilon_y$ (ε is emittance)

Peak Brilliance ~ $I / \varepsilon_x \varepsilon_y \tau$ (τ is bunch length)

Coherent Flux ~ $I / \varepsilon_x \varepsilon_y$

Photon Degeneracy ~ $I / \varepsilon_x \varepsilon_y \tau$

Thus, I, ε_x, ε_y, τ are fundamental.

Storage Rings Limit Experiments

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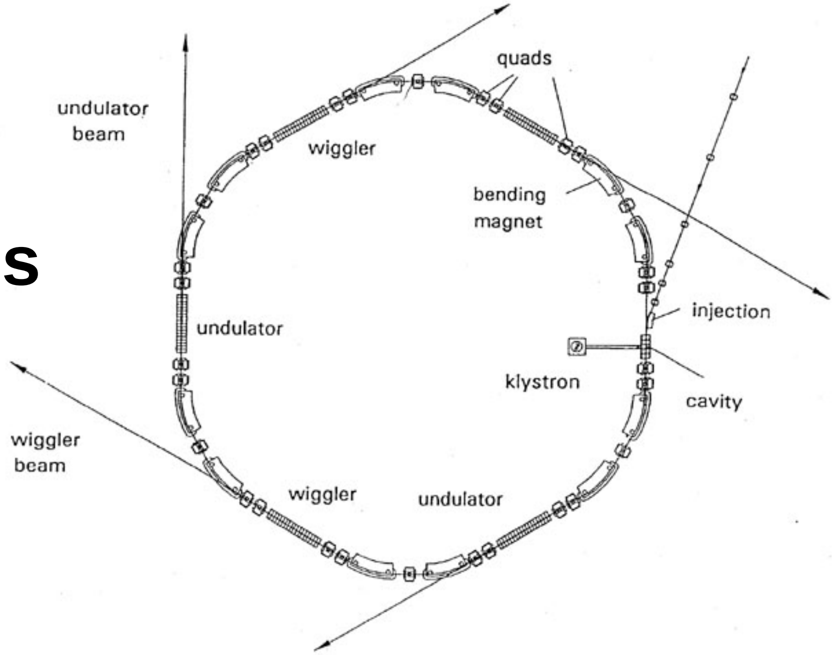
- All existing hard x-ray SR facilities use storage rings to produce x-rays.



- Storage rings technology is well-developed.

- Upgrading is difficult.

- An <u>unavoidable</u> consequence of storage is that the electron bunches are degraded, limiting the brilliance, coherence, pulse length, size, and time structure of the x-ray beams.

Storage rings technology at hard physical limits. Much brighter storage rings not feasible.

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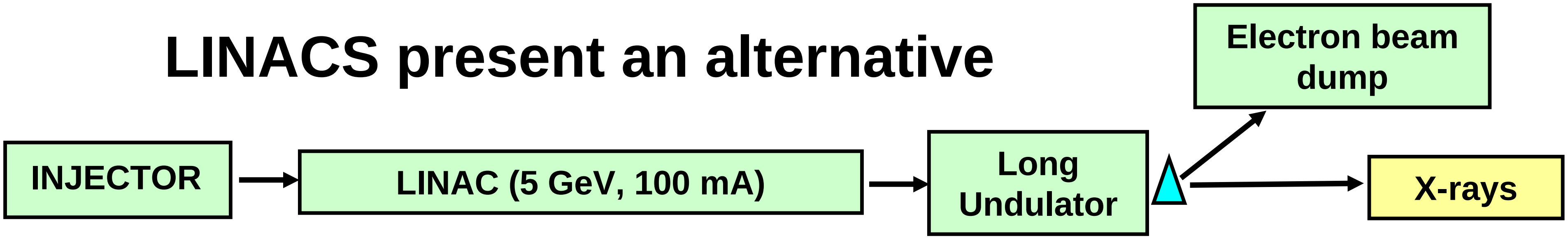
LINACS present an alternative


INJECTOR

LINAC (5 GeV, 100 mA)

Long Undulator

Electron beam dump

X-rays

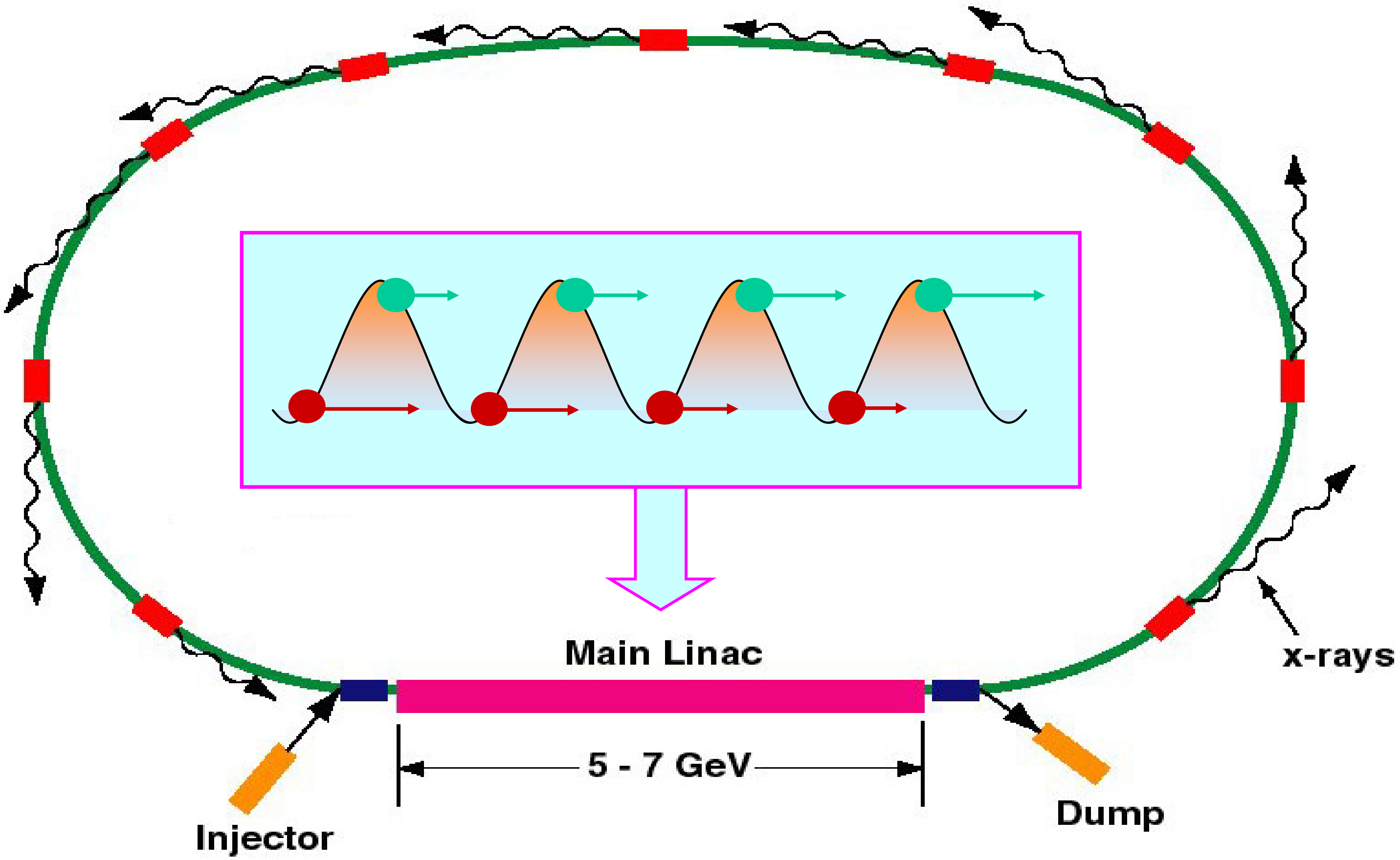
Advantages:

- Injector determines emittances, pulse length, current.
- Complete flexibility of pulse timing & structure.
- Small source size ideal for nanoprobes
- No fill decay.

Disadvantage: You’d go broke!!

(5 GeV) x (100 mA) = 500 MW!!

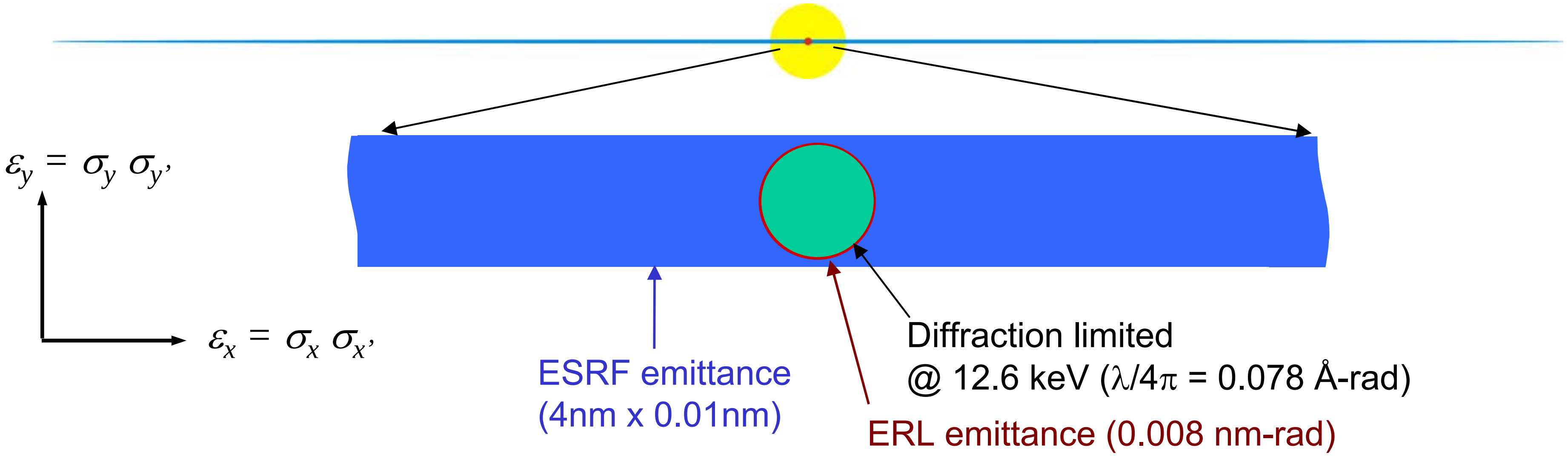
Energy Recovery Linac



- ● Accelerating bunch
- ● Returning bunch

A superconducting linac is <u>required</u> for high energy recovery efficiency

Transverse & Longitudinal Properties



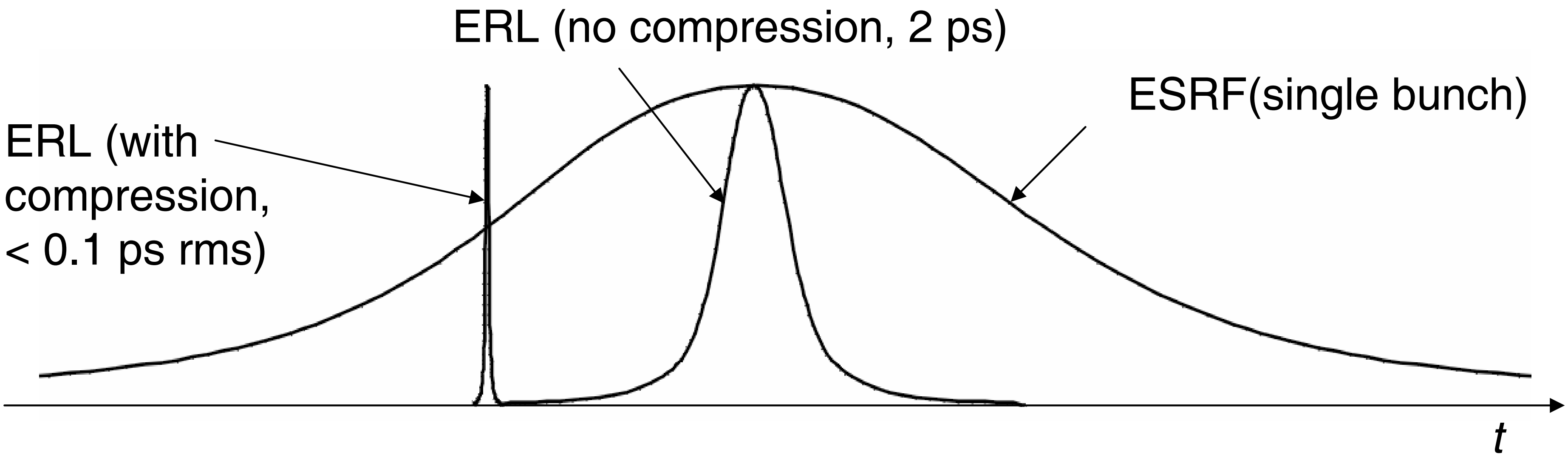
$\varepsilon_y = \sigma_y \sigma_{y'}$

$\varepsilon_x = \sigma_x \sigma_{x'}$

ESRF emittance
(4nm x 0.01nm)

Diffraction limited
@ 12.6 keV ($\lambda/4\pi$ = 0.078 Å-rad)

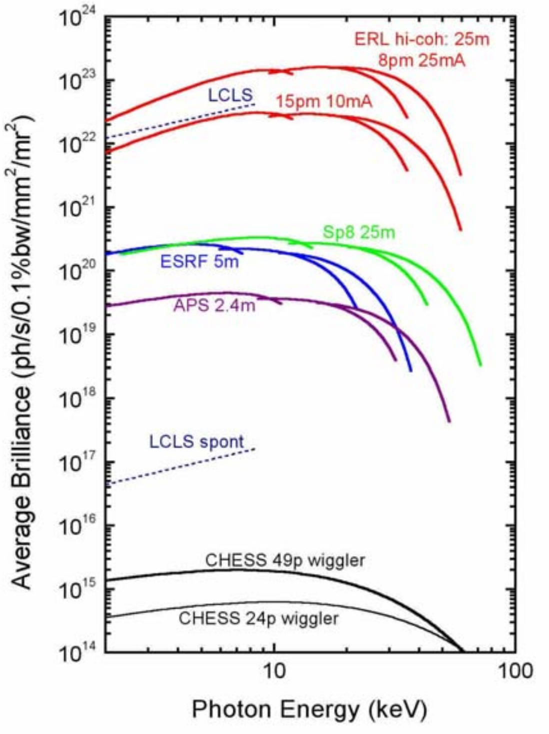
ERL emittance (0.008 nm-rad)

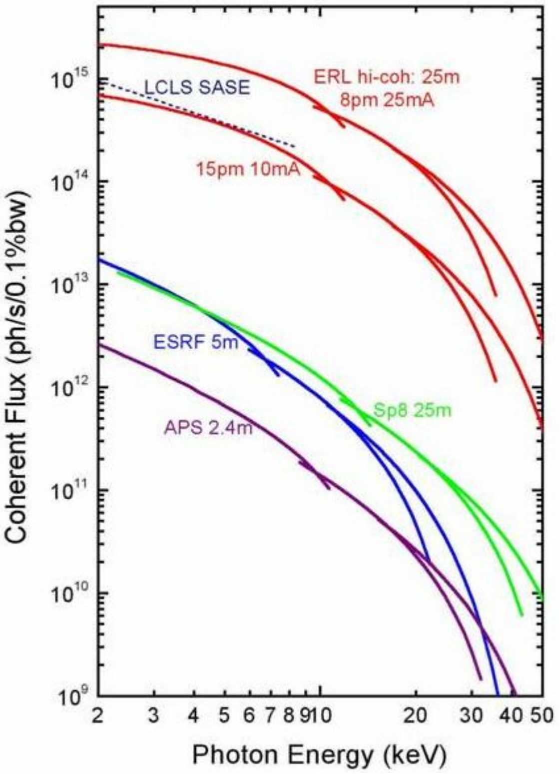


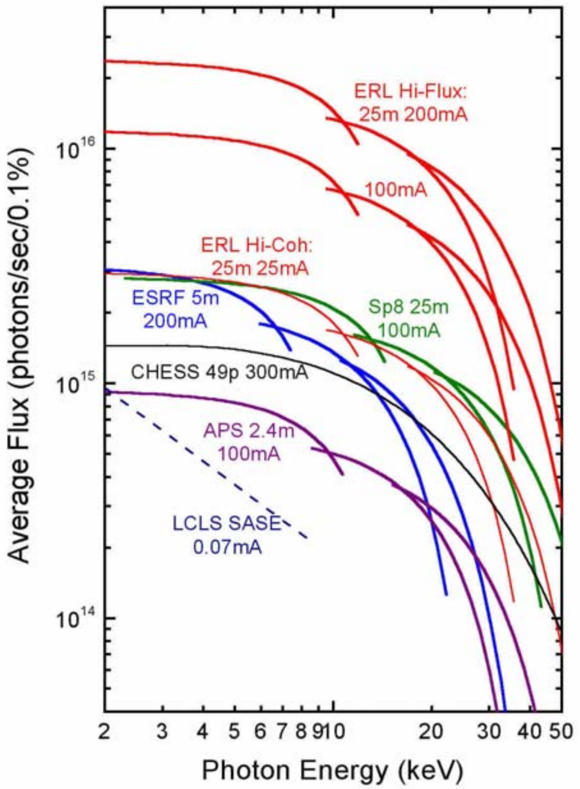
ERL (no compression, 2 ps)

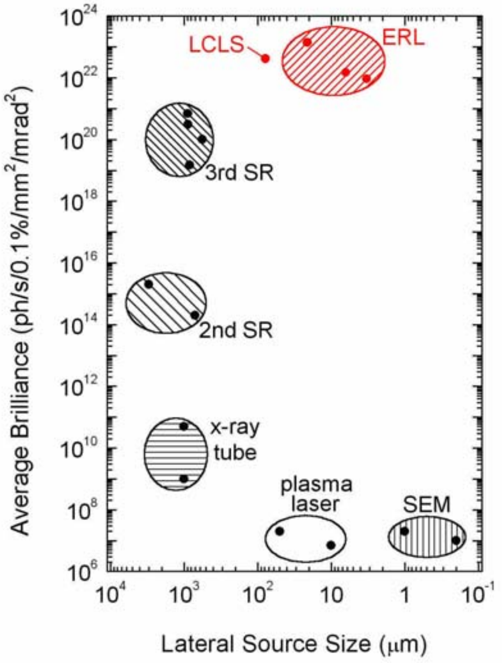
ESRF(single bunch)

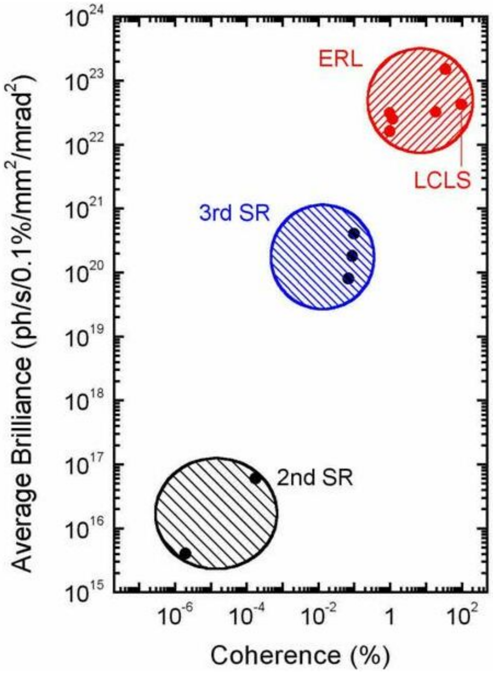
ERL (with
compression,
< 0.1 ps rms)


Average Brilliance (ph/s/0.1%bw/mm^2/mr^2)
Photon Energy (keV)
10^{24}
10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10
100
ERL hi-coh: 25m
8pm 25mA
LCLS
15pm 10mA
Sp8 25m
ESRF 5m
APS 2.4m
LCLS spont
CHESS 49p wiggler
CHESS 24p wiggler


Coherent Flux (ph/s/0.1%bw)
Photon Energy (keV)
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
2
3
4
5
6
7
8
9
10
20
30
40
50
LCLS SASE
ERL hi-coh: 25m
8pm 25mA
15pm 10mA
ESRF 5m
Sp8 25m
APS 2.4m


Average Flux (photons/sec/0.1%)
Photon Energy (keV)
10^{16}
10^{15}
10^{14}
2
3
4
5
6
7
8
9
10
20
30
40
50
ERL Hi-Flux:
25m 200mA
100mA
ERL Hi-Coh:
25m 25mA
ESRF 5m
200mA
Sp8 25m
100mA
CHESS 49p 300mA
APS 2.4m
100mA
LCLS SASE
0.07mA


Average Brilliance (ph/s/0.1%/mm^2/mrad^2)
Lateral Source Size (μm)
10^{24}
10^{22}
10^{20}
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
LCLS
ERL
3rd SR
2nd SR
x-ray
tube
plasma
laser
SEM


Average Brilliance (ph/s/0.1%/mm^2/mrad^2)
Coherence (%)
10^{24}
10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
ERL
LCLS
3rd SR
2nd SR

Advanced Photon Source compared with Energy Recovery Linac

Parameter	**APS 3rd generation storage ring**	**Energy recovery linac**	**Gain factor**
Electron source size in microns rms	239(h) x 15(v)	2(h) x 2(v)	1/900 in area
Micro x-ray beamsize	100 nm to 1 micron	1 nm	100 to 1000
Coherent flux x-rays/sec/0.1% bw	3 x 10^{11}	9 x10^{15}	3,000
Pulse duration (rms)	32 ps	<100 fs	more than 320 times shorter

Conclusion: the ERL machine will be transformational!

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THREE REASONS TO DEVELOP ERL TECHNOLOGY

1. ERLs can do everything possible at most advanced 3rd gen SR sources, thus meeting growth in demand for SR. As opposed to XFELs, a huge ERL user community already exists.
2. ERLs additionally enable SR experiments not now possible due to high ERL brilliance, coherence, short pulses and flexible bunch structure. These include new regimes of
   - Microbeam diffraction and fluorescence
   - High pressure diffraction and spectroscopy
   - Femtosecond x-ray studies of solids, molecules and proteins
   - Coherent imaging and microscopy
   - Photon correlation spectroscopy
   - Nuclear resonant scattering
   - Inelastic x-ray scattering
   - Normal diffraction, x-ray metrology, and x-ray interferometry
   - Polarized x-ray beam studies, resonant scattering and circular magnetic dichroism studies
3. The inherent limits of ERLs are not yet known. Injector improvements may be expected, providing an attractive upgrade pathway.

Goals of Cornell ERL Project

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- Initial R&D on ERLs. (completed)
- Build, test critical modules to resolve machine issues. Phase I (in process)
- Design and build a high energy (5-7 GeV) ERL x-ray facility at Cornell as an upgrade to CESR. Phase II (future)
- Perform experiments, R&D on ERLs, in context of a user facility. (future)

5GeV ERL Upgrade for CESR

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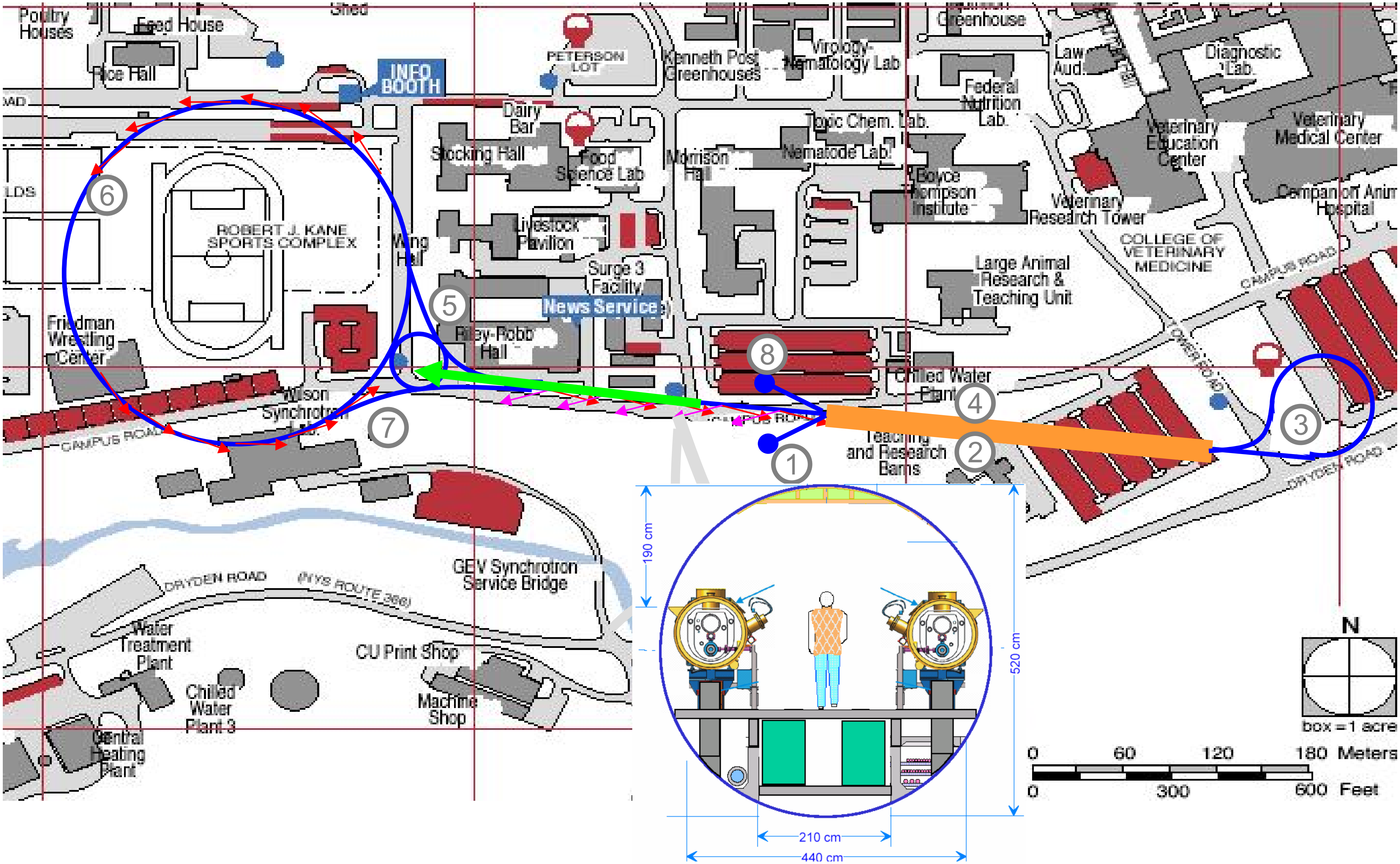
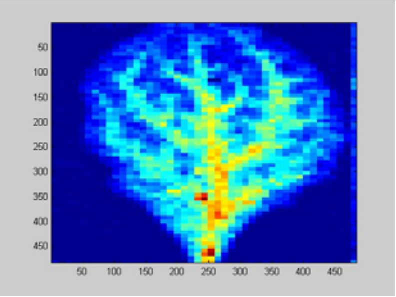
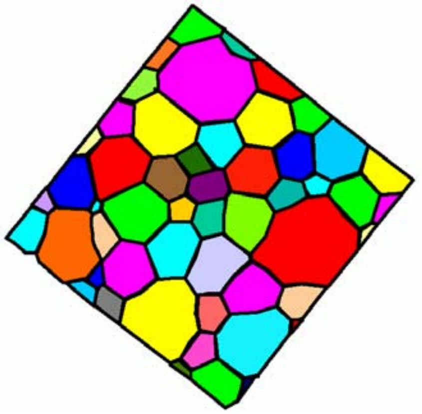


Microbeam X-ray Science



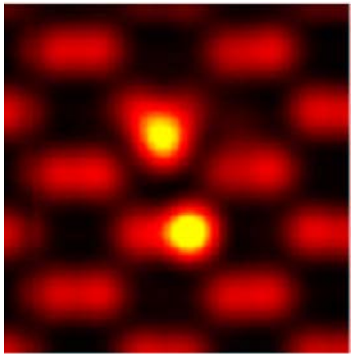
Zinc distribution in plant leaf by SR x-ray fluorescence

few cm scale object (CHESS data)



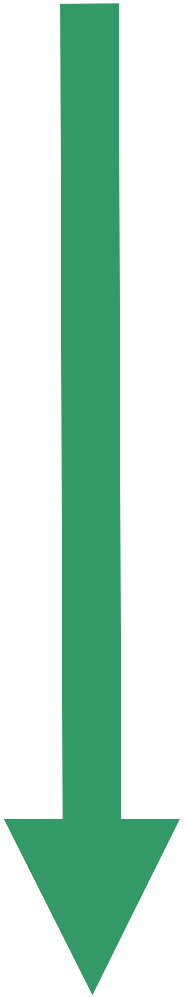
Hot-rolled Aluminum

SR x-ray diffraction. Map grain orientation and stress in real samples of 10^4 cubic microns at 1 micron resolution (APS data)



Two impurity atoms (yellow dots) in silicon crystal

TEM with 200 keV electrons can see individual atoms on samples a few atoms thick (Voyles, Lucent Technologies)



Centimeter scale

Micron scale

Nanometer scale

Atomic scale

ERL Provides Unprecedented Nanobeams

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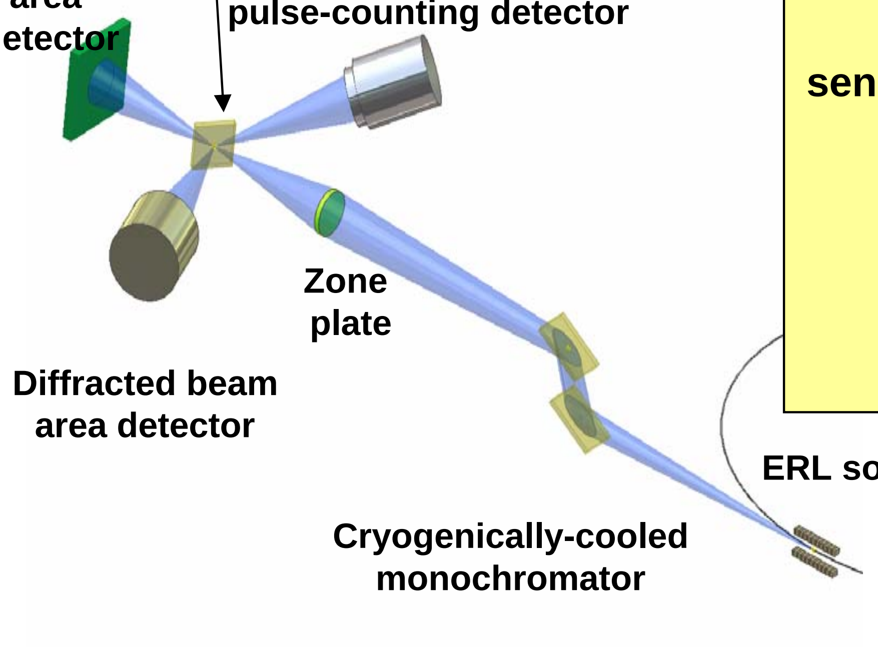
Storage ring nanobeam flux limited by source size, shape, and divergence.

- 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)



Sample

Transmitted beam area detector

Energy-dispersive, pulse-counting detector

Zone plate

Diffracted beam area detector

Cryogenically-cooled monochromator

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.

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

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

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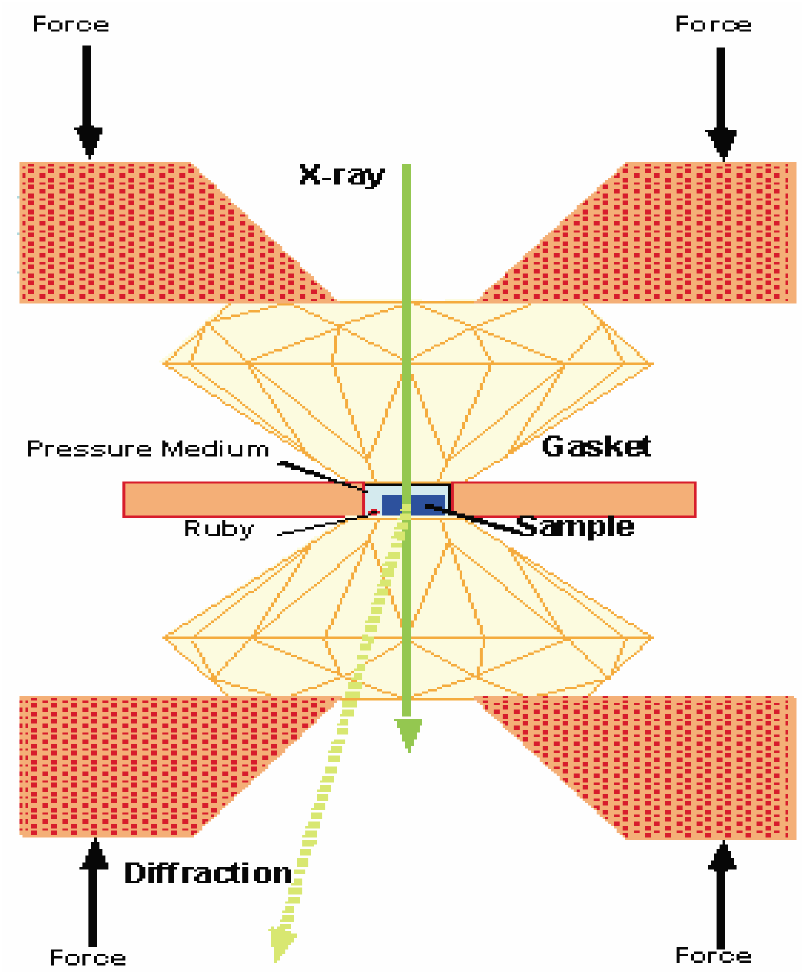
- **HP experiments are brightness-limited. Time resolved experiments for plasticity, rheology measurements, phase transitions, etc. are especially photon starved.**
- **Higher P ⇒ smaller samples.**
- **No ideal pressurization medium ⇒ need to scan sample.**
- **Peak-to-background critical.**
- **ERL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



Parise, Hemley & Mao

High Pressure Science Areas Expanded by ERL

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- **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

Biological and Polymer Science:

Structural dynamics of macromolecular solutions

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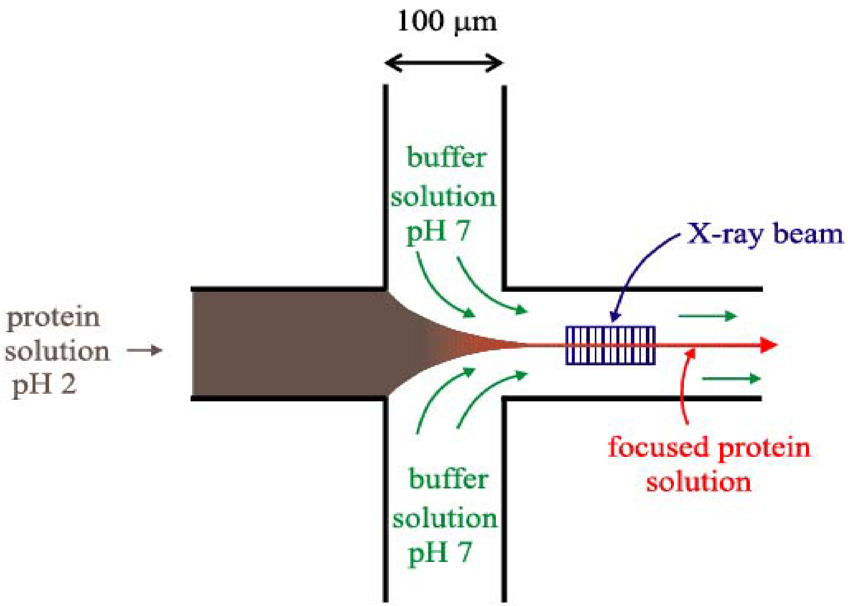
- Examples: folding/unfolding of proteins & RNA; assembly of fibers; polymer collapse upon solvent changes; conformational changes upon ligand binding; monomer/multimer association.
- Microfabricated laminar flow cells access microsecond equilibration mixing times.
- Data acquisition entirely limited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

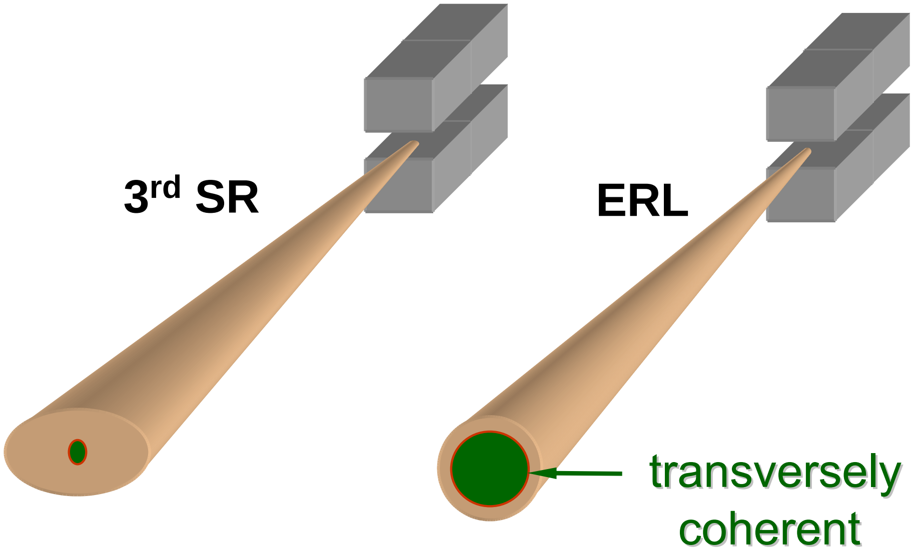


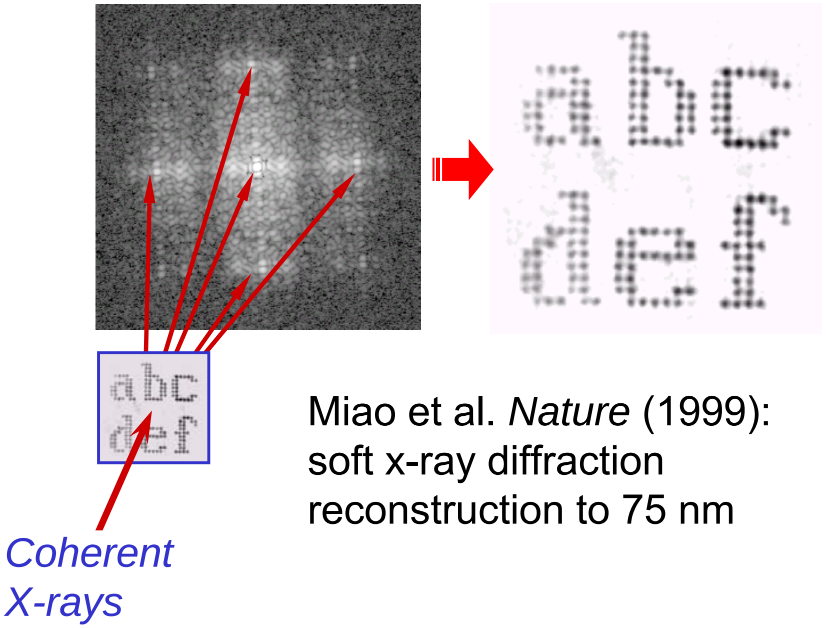
Thanks to Lois Pollack

Cornell Univ.

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

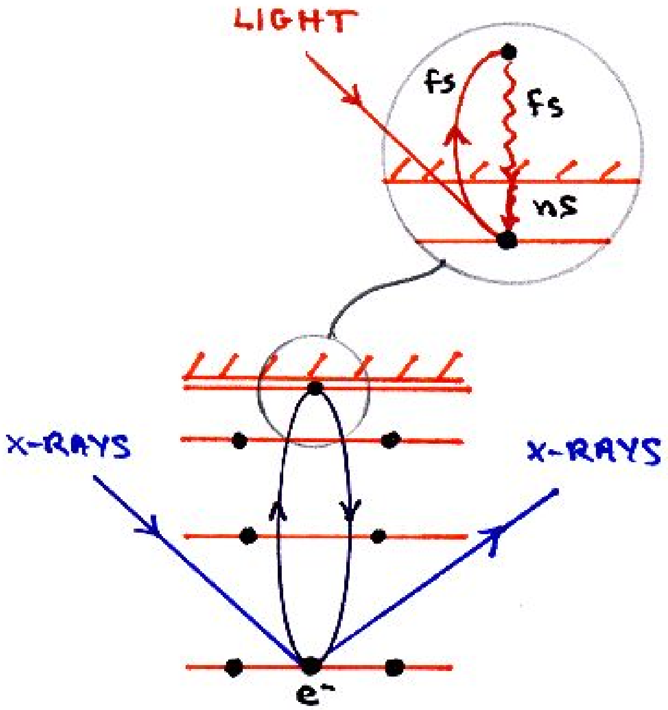


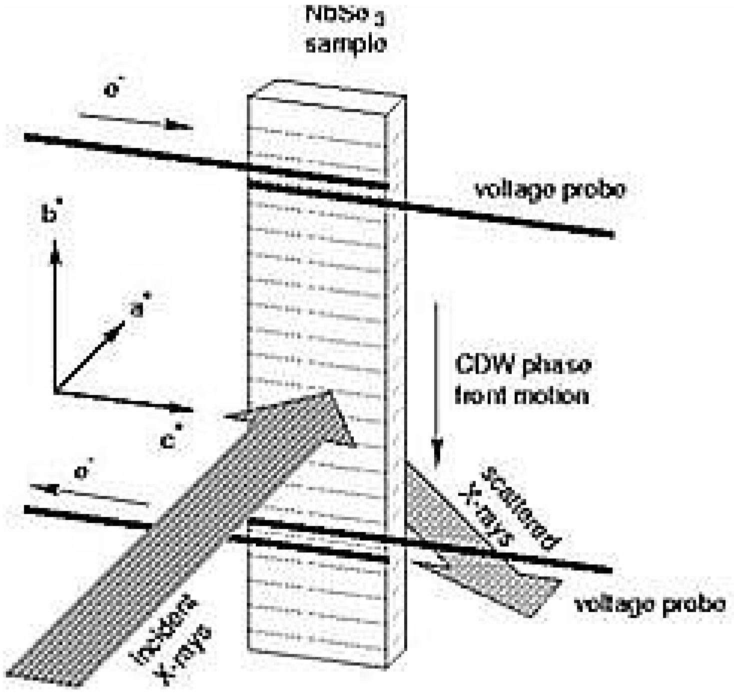


Miao et al. *Nature* (1999): soft x-ray diffraction reconstruction to 75 nm

- 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

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.

Magnetic Switching in 'Nanomagnet' Array

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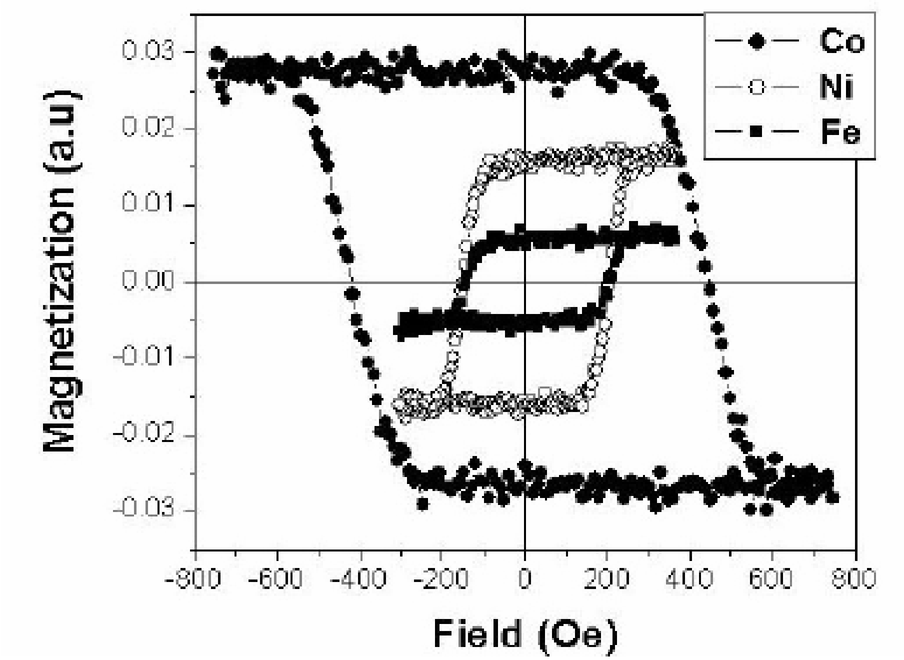
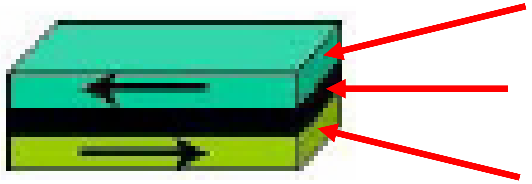
work at X13A at NSLS by F.J. Castano, et.al J. Appl. Phys. 93, 7927 (2003)



Circular Magnetic X-ray Dichroism (CMXD), at L-edges → element specific measurement of magnetic hysteresis. This model system is being studied to help optimize structures for future high density MRAM data storage.

Today large arrays of multilayers are required for signal. CMXD + zone plate focusing (being explored at APS 1ID) will combine to form a powerful CMXD microscope at future ERL sources

An ERL would allow data to be collected on a single structure instead of millions of structures in 1cm x 1cm area



Cobalt (hard magnetic layer)
4 nm thick

Copper (3 nm)

Ni/Fe (soft magnet)
(6 nm)

individual nanomagnet
of 70 nm x 550 nm

Simulated Coherent Diffraction Data

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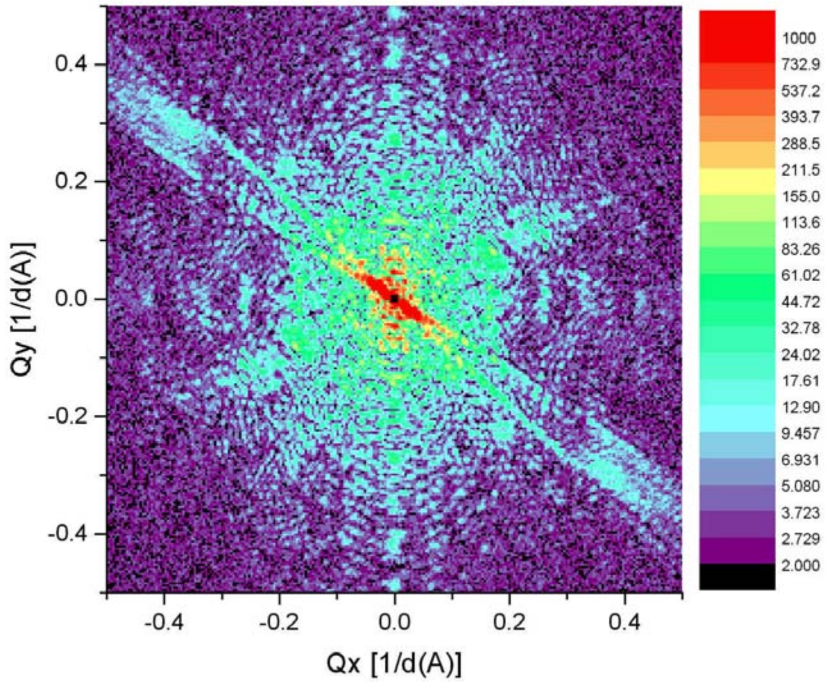
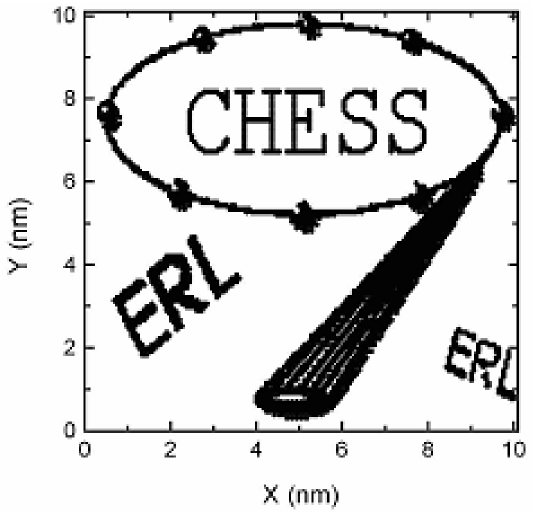


Shen, Bazarov & Thibault., Cover image of Journal of Synchrotron Radiation **11**, 371 (2004) from about 3,000 gold atoms on a 10 nm x 10 nm square

Phase retrieval by iterative medhods 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

ERL Enables Following Structure of Ultrafast Chemical Reactions

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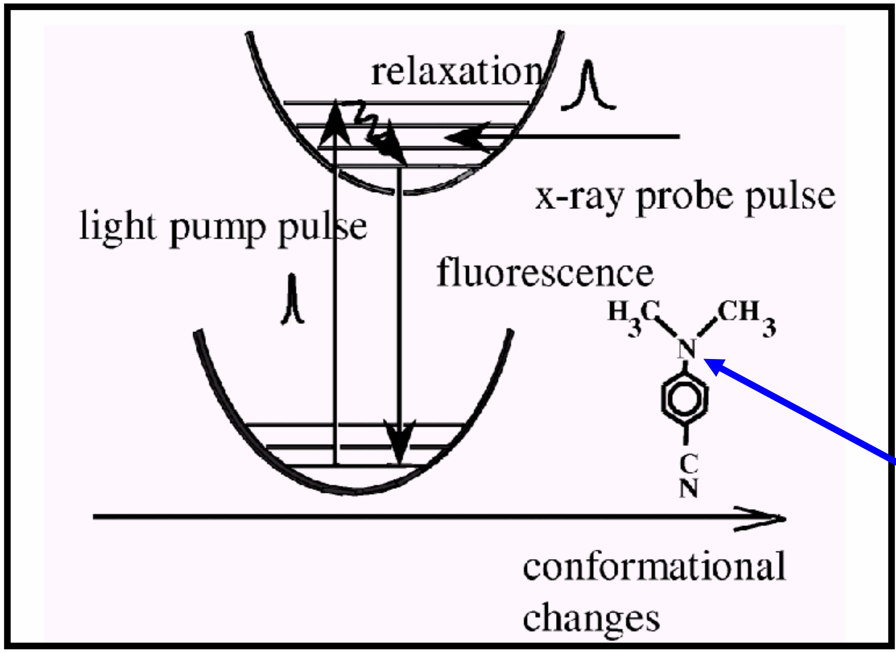
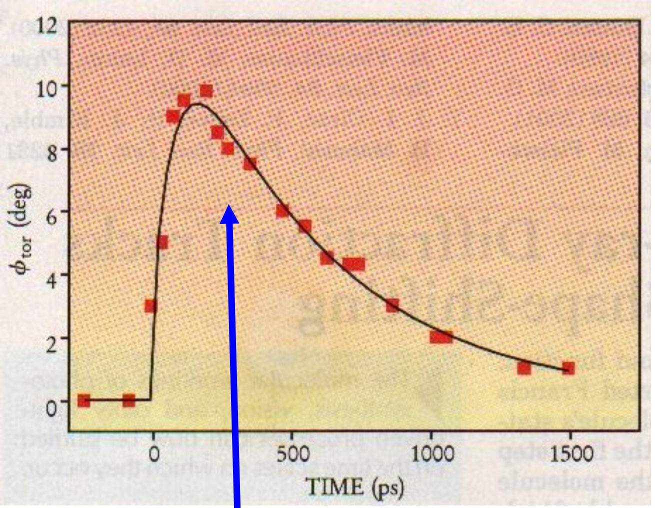
Scientific challenge is to understand the structural evolution of the “transition state(s)” intermediate between reactant and product species.

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

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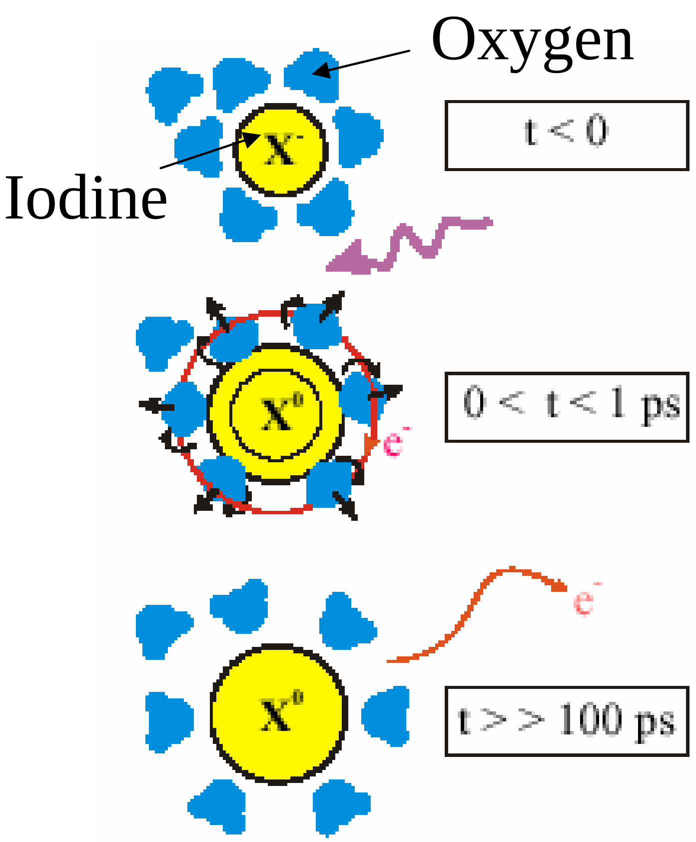

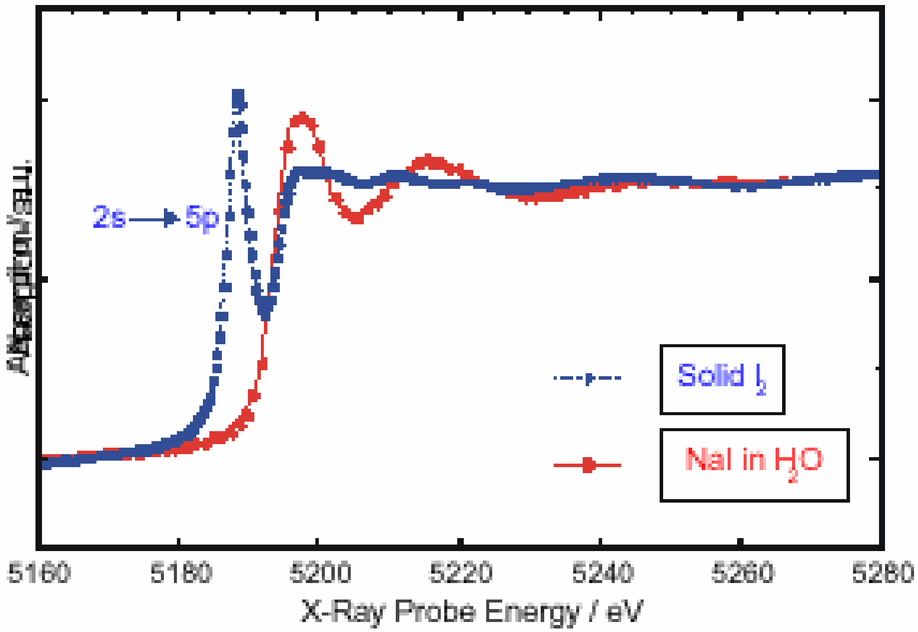

Schematic illustration of Photo-neutralization of I- in liquid phase. EXAFS of 2*s* → 5*p*. Change in spectra arises from changed I-O distances. (From Schoenlein & Falcone).

ERL would allow examination of intermediate states and to develop structural models of what really happens during hydration!

Atom-sized X-ray Beam Applications

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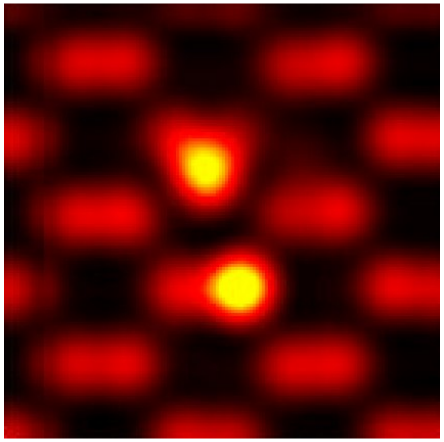
Microelectronics application:
Debug transistors and IC at the smallest line widths where increasingly high-dopant density favors formation of electrically inactive clusters (a problem!)



- 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.

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END