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Energy Recovery Linac (ERL) Overview

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1. **ERL Idea and Properties**
2. **Scientific Motivation**
3. **Status of ERL Projects**

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SR demand is growing. Why not simply build more storage rings?

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Answer: There is a need for more flexible SR sources with better capabilities.

- **Long lead times**. They typically take 5-10 yrs to plan & build.
- **Expense**. Even modest 3rd generation x-ray SR facilities cost hundreds of millions of dollars.
- Storage ring beams have **fundamental limitations** and are at the **point of diminishing returns**. In consequence, many experiments cannot be done at storage rings.

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What do we ideally want from a SR source?

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1. **High average <u>and</u> high peak**
   - Brilliance (phot/s/0.1% bw/mrad^2/mm^2)
   - Brightness (phot/s/0.1% bw/mrad^2)
   - Flux (phot/s/0.1% bw)

2. **Flexible pulse structure.**
   - Programmable pulse trains (interval, bunch size)
   - Adjustable pulse lengths down to the femtosecond regime

3. **Small x-ray source size of desired shape, e.g., circular.**

4. **Flexibility of source operation.**
   - No fill decay
   - Stability & robustness
   - Easily upgraded (reset the point of diminishing returns)

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These desirable characteristics depend on fundamental facts of SR

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Flux ~ I (current)

Brilliance ~ $I / \bar{\varepsilon}_x \bar{\varepsilon}_y$ (ε is emittance)

Peak Brilliance ~ $I / \bar{\varepsilon}_x \bar{\varepsilon}_y \tau$ (τ is bunch length)

Coherent Flux ~ $I / \bar{\varepsilon}_x \bar{\varepsilon}_y$

Photon Degeneracy ~ $I / \bar{\varepsilon}_x \bar{\varepsilon}_y \tau$

Thus, I, ε_x, ε_y, τ are fundamental.

Storage Ring Limitations

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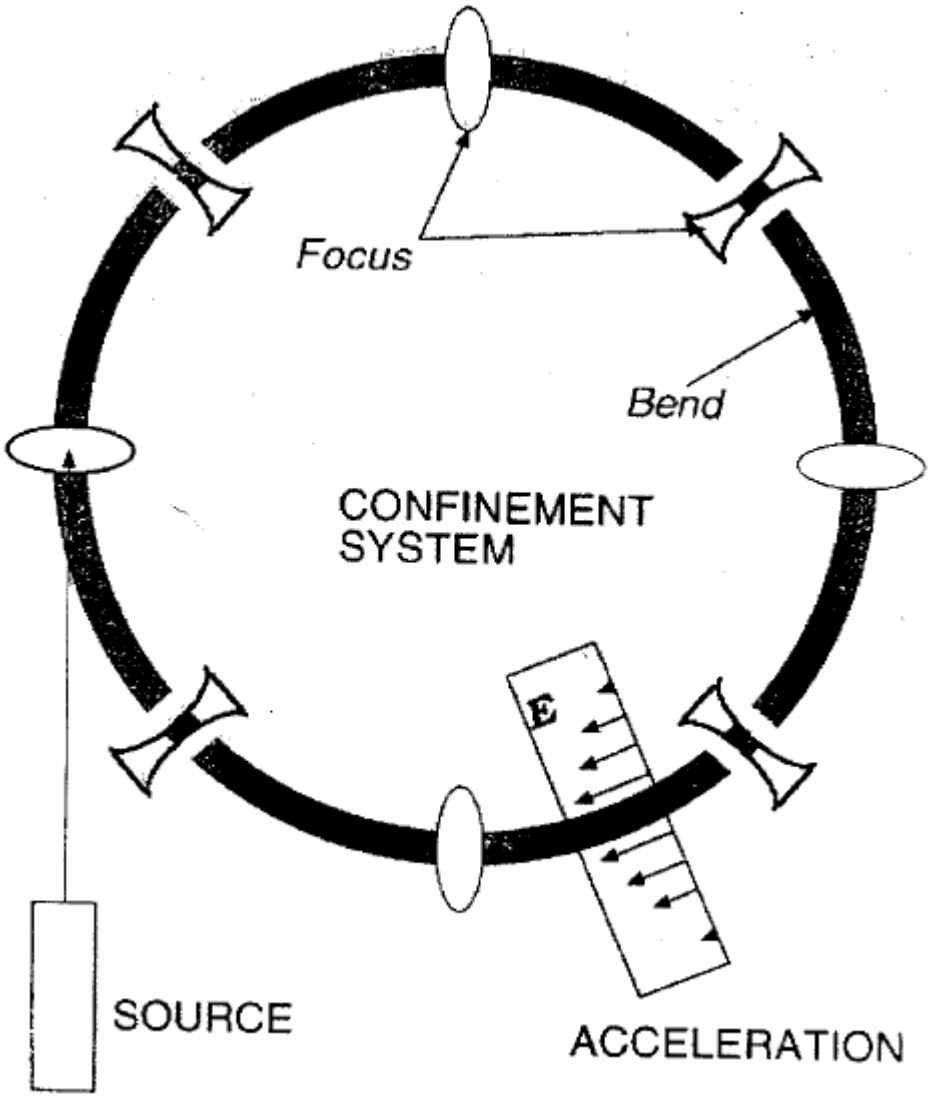


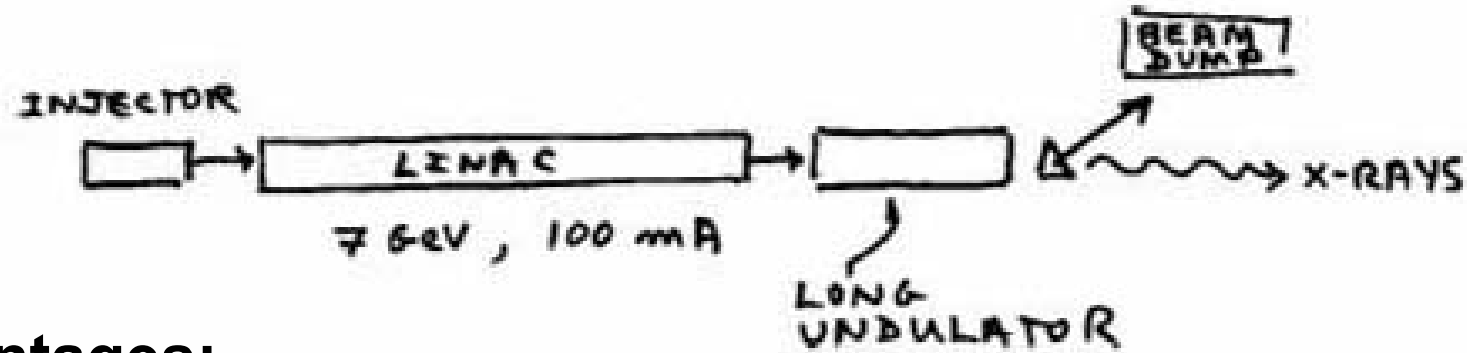
Transverse effects of magnetic focusing, SR & RF
⇒ equilibrium emittance, ε, after ~10^4 revolutions.

Longitudinal effects of phase focusing, stochastic SR mission & energy loss, and RF
⇒ equilibrium bunch length, τ.

Interparticle effects (e.g., Touschek effect) & population of tails of cross-sectional distribution
⇒ Limit current, I, lifetime.

So ε, τ, I are all affected!!

Linacs present an alternative



Advantages:

- **Injector determines emittances, pulse length, current.**
- **Complete flexibility of pulse timing, structure.**
- **No fill decay.**

Disadvantage: You'd go broke!!

(7 GeV) x (100 mA) = 700 MW!!

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Solution: Use energy recovery. First proposed by Tigner in 1965.

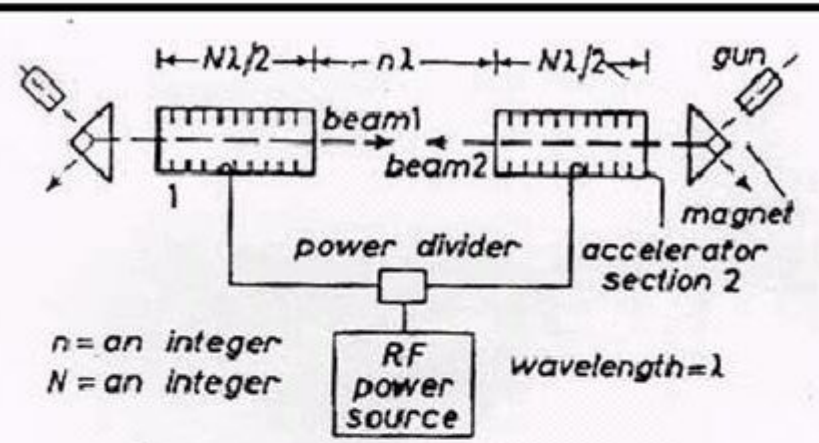

Fig. 2.

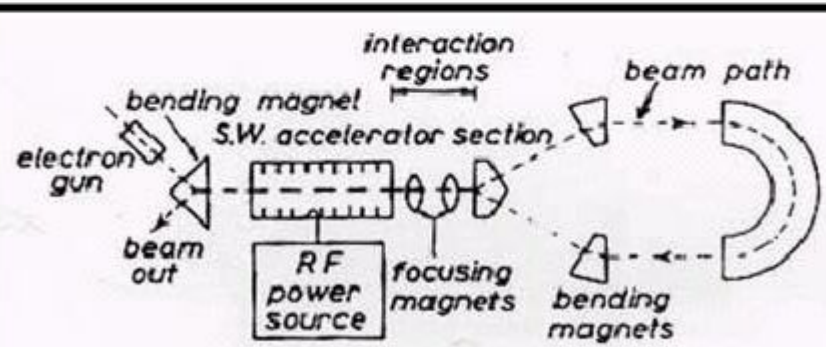

Fig. 3.

M. Tigner, Nuovo Cimento 37 (1965)1228.

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Energy Recovery Linac idea

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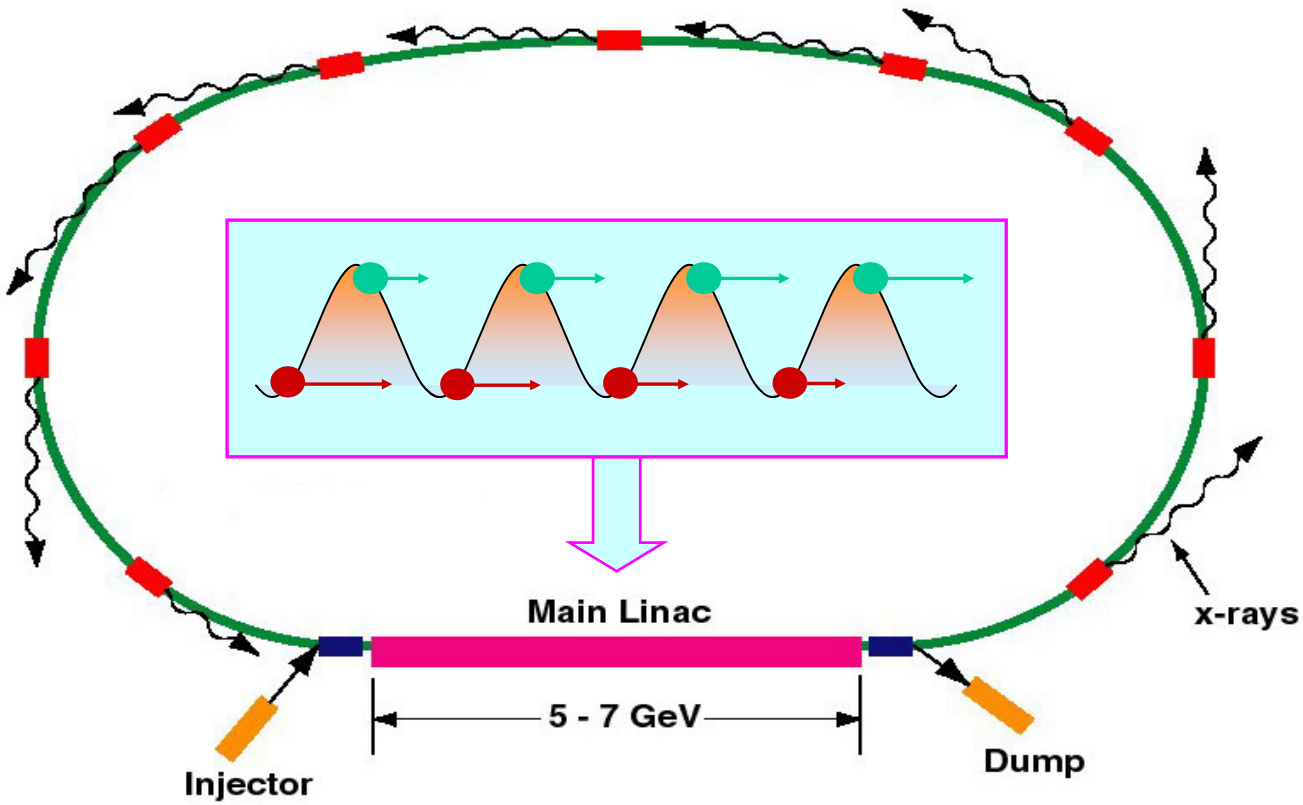

- Accelerating bunch
- Returning bunch

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Proof of principle

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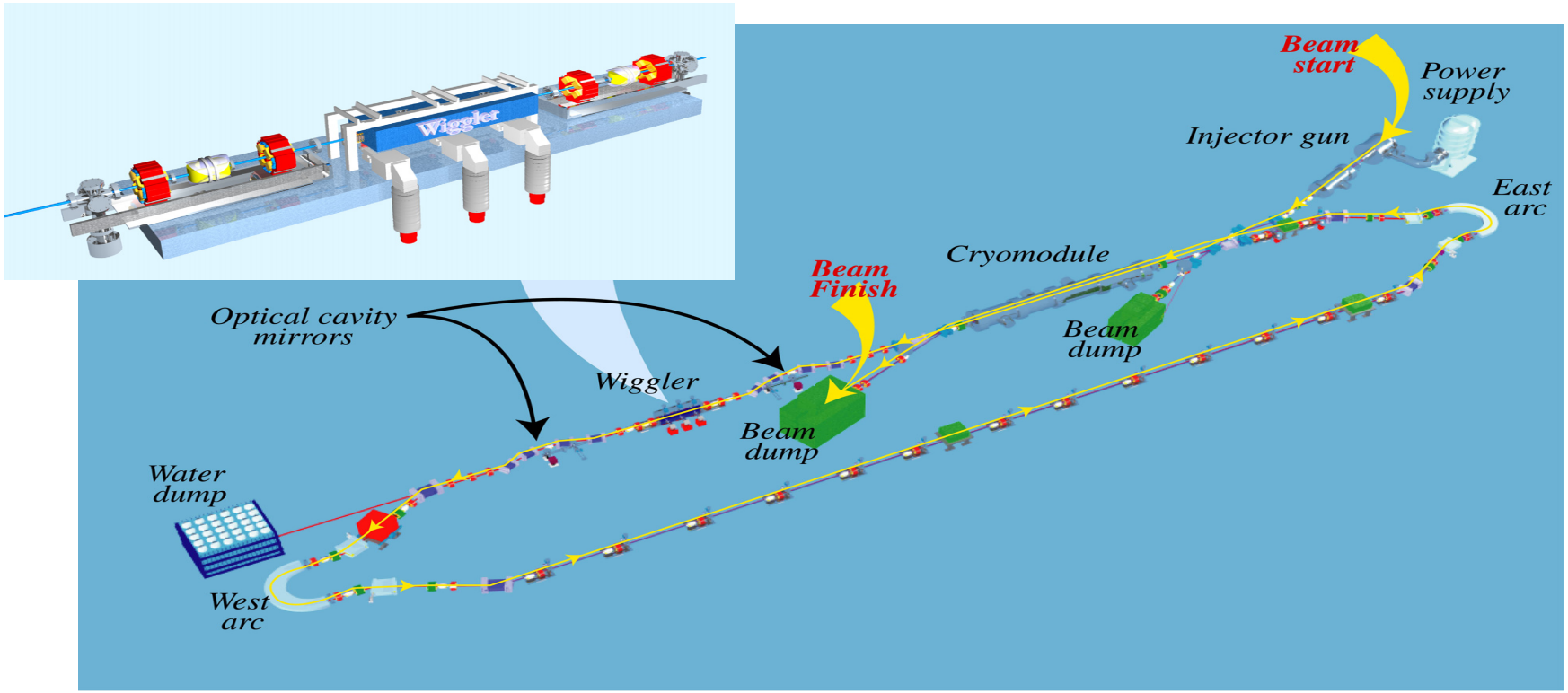
- First demonstrated at Stanford SCA/FEL [Smith et al., *NIM A* **259**, p. 1-7 (1987)]
- IR FEL Project at JLAB. (See also, talk 3.4, 4:00 today)



I_{ave} = 5 mA $\varepsilon_n \geq 7$ μm

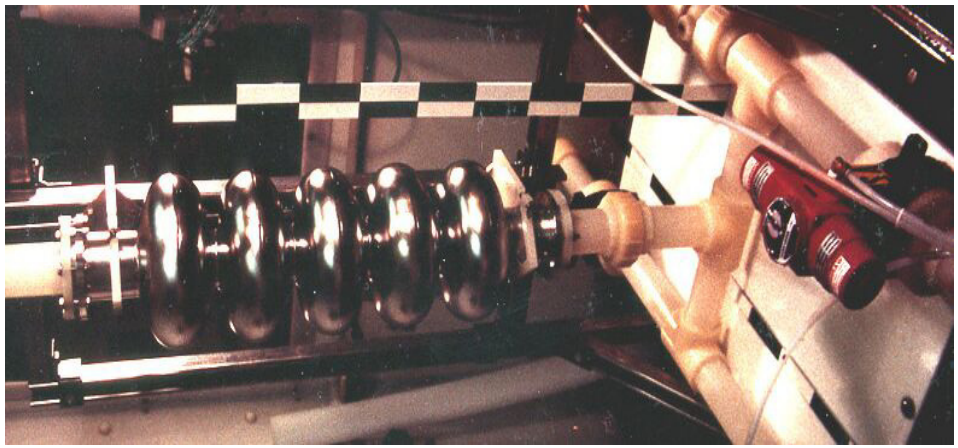
E_{max} = 48 MeV $\sigma_l > 330$ fs

*G. R. Neil, *et al., Physical Review Letters,* **84,** 622 (2000)

10 mA, 210 MeV upgrade is in the works

Two key technologies for ERL

Superconducting RF cavities
(Want Q ~ 10^{10} @ 20 MV/m)



First TESLA 5-cell cavity undergoing chemical processing at Cornell's SRF development facility

Laser-driven photoinjector
(Want ε_n ~ μm @ 100 mA)

DC photogun at JLAB IR FEL
(courtesy of JLAB)

ERL Flexibility

1 km ERL: 1,000m

1 km Storage Ring, 12 Hr fill: 13,000,000,000,000m

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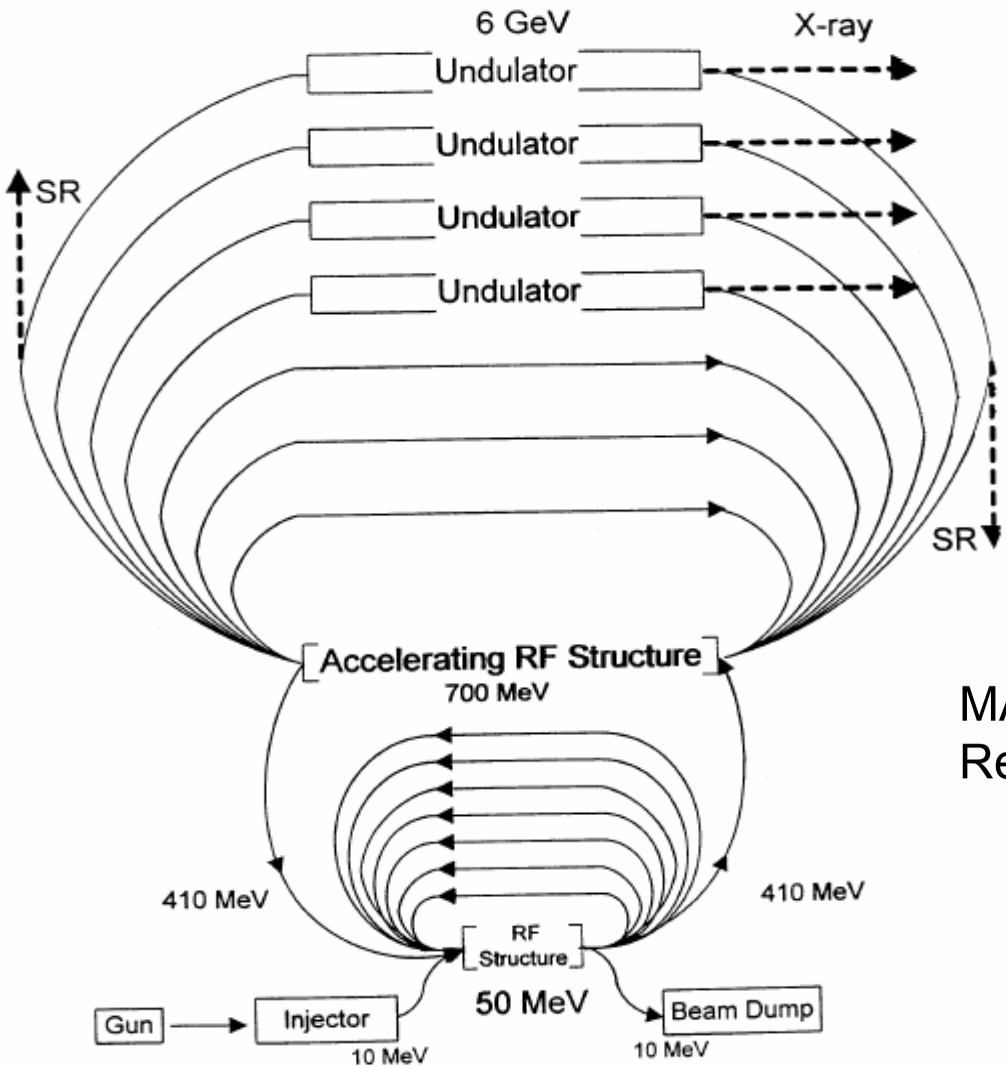

MARS (Multiturn Accelerator-Recuperator Source), Budker Inst., Novosibirsk.

(From: G. Kulipanov)

NSLS Photo-injected Energy Recovery Linac (PERL), Daresbury 4GLS

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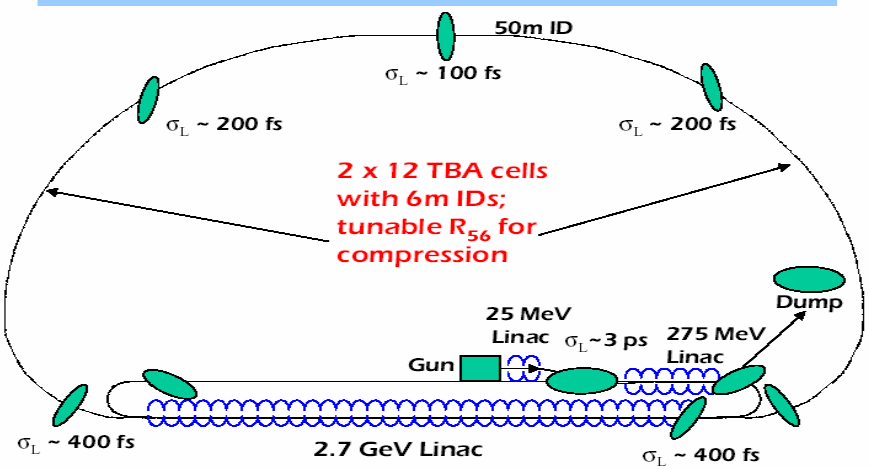
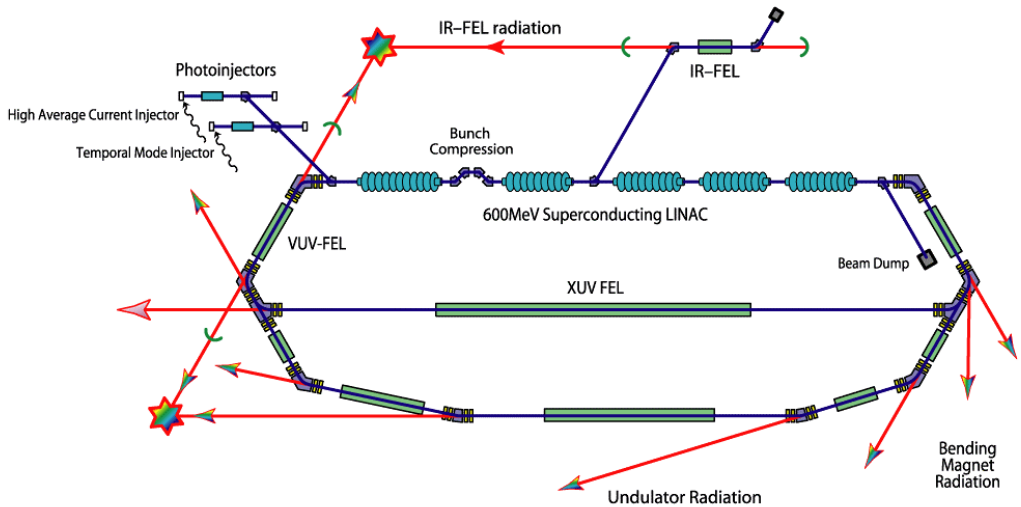
Strawman Layout for a 3 GeV PERL



Thanks to Jim Murphy

4GLS



ERL Properties

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Goals of Cornell ERL Project

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- Initial R&D on ERLs.
- Build, test a Phase I machine (e.g., 100 mA, 100 MeV) to resolve machine issues. The initial design was a collaboration between Cornell's CHESS and LEPP Centers and the Thomas Jefferson National Accel. Facility.
- Design and build a high energy (5-7 GeV) Phase II ERL x-ray facility.
- Perform R&D on utilization of ERLs and their electron and x-ray beams.

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Preliminary Design Parameters of ERL

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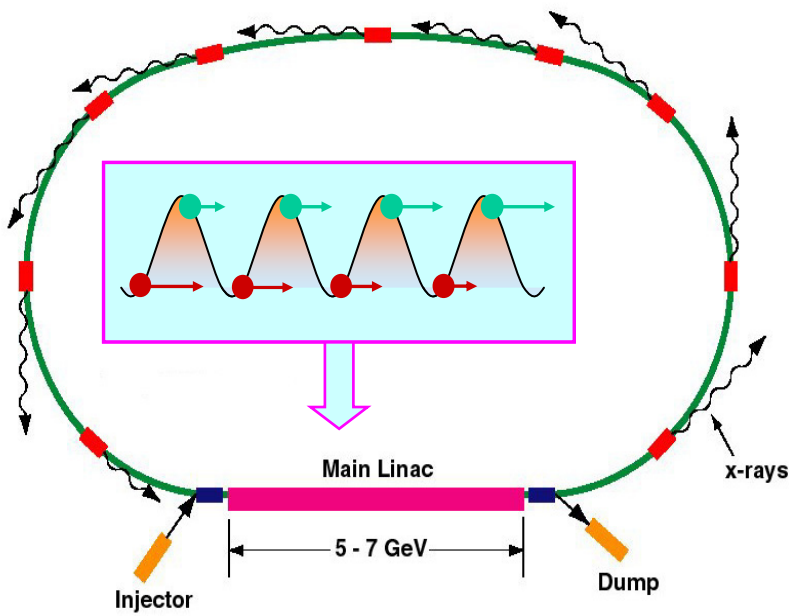
		ERL high-flux	ERL high-coherence
Machine design	Energy E_G (GeV)	5.3	5.3
	Current I (mA)	100	10
	Charge q (nC/bunch)	0.077	0.008
	ε_x (nm-rad)	0.15	0.015 *
	ε_y (nm-rad)	0.15	0.015 *
	Bunch fwhm τ (ps)	0.3 – 5	0.3 – 5
	# of bunches f (Hz)	$1.3 \cdot 10^9$	$1.3 \cdot 10^9$
Insertion device	Undulator L (m)	25	25
	Period λ_u (cm)	1.7	1.7
	# of period N_u	1470	1470
	Horizontal β_x (m)	12.5	4.0
	Vertical β_y (m)	12.5	4.0
	Undulator K @ E_1	1.38	1.38
	1st harmonic E_1 (keV)	8.0	8.0



- Accelerating bunch
- Decelerating bunch

* Assuming emittance scales with bunch charge.

Expected Brilliance

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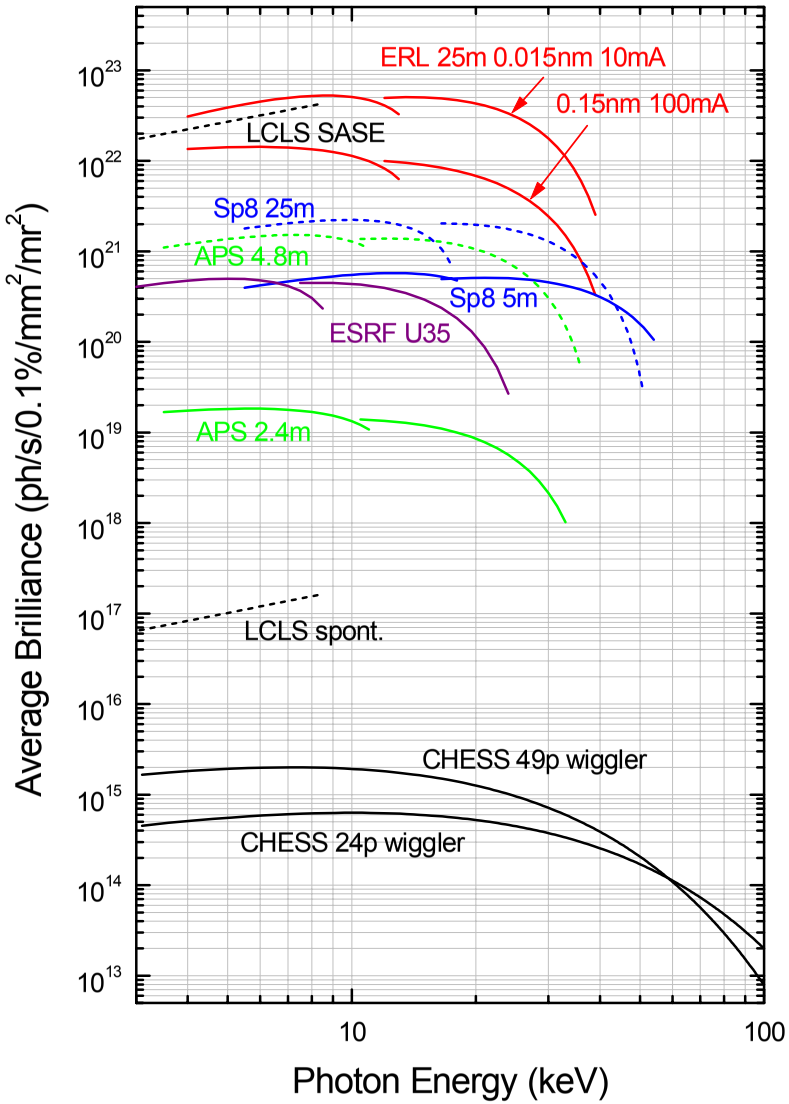
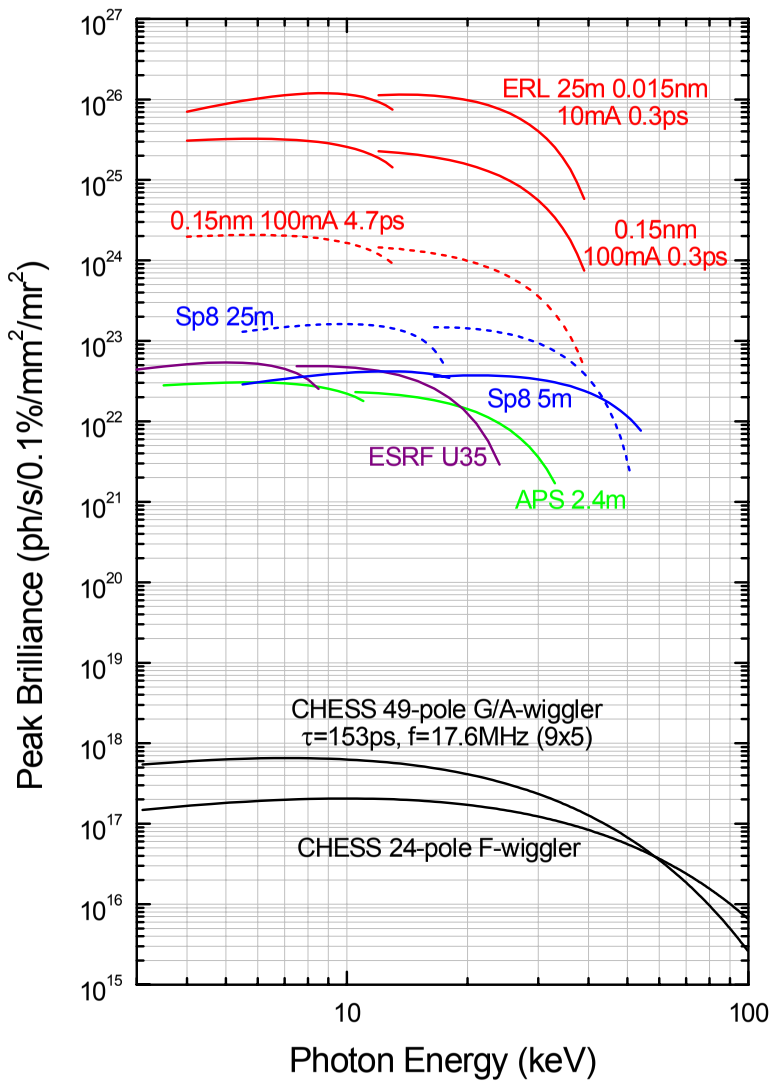
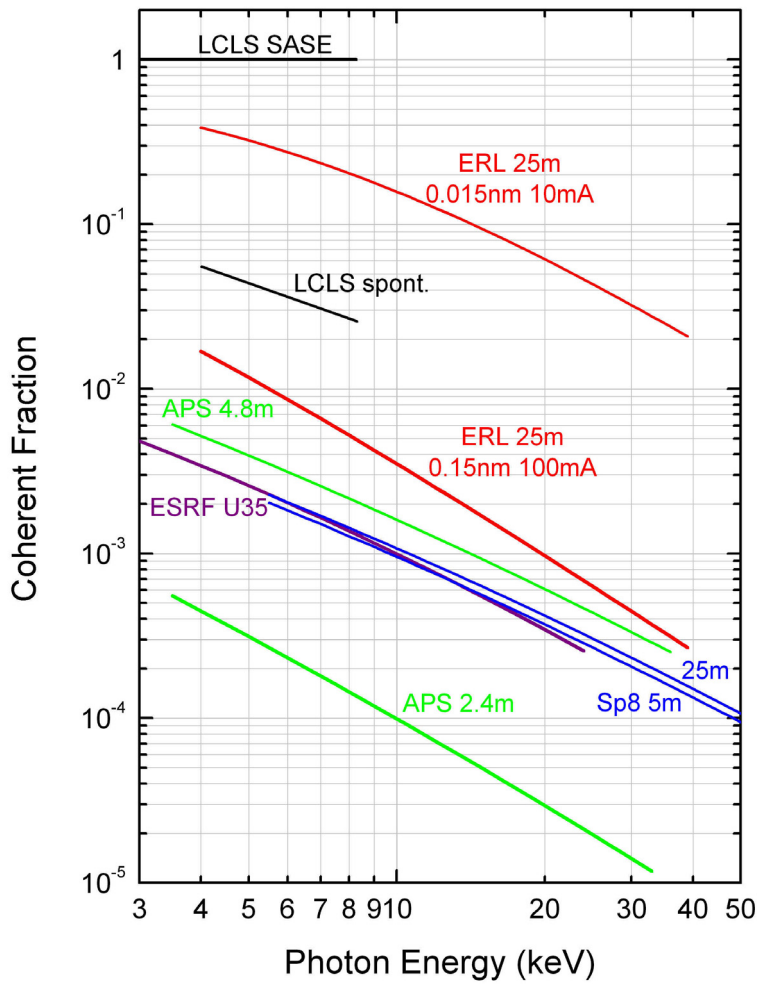




ERL Transversely Coherent Flux



- Time-averaged coherent flux comparable to LCLS XFEL
- Coherent fraction ~100x greater than 3rd SR sources
- Peak coherent flux (coherent flux per pulse) ~1000x greater than 3rd SR sources, if brilliance can be preserved with short pulses.

ERL Transverse Coherence

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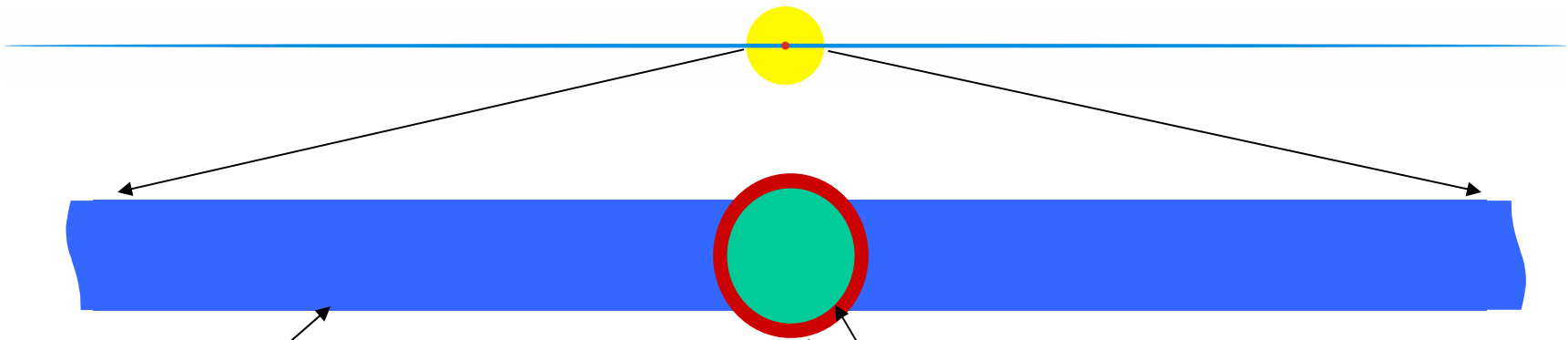
Brilliance goes as $\alpha \equiv (\bar{\varepsilon}_x \bar{\varepsilon}_y)^{-1}$, so the emittance product needs to be small.



ESRF emittance
(4nm x 0.01nm)
i.e., α = 25 nm^{-2}

Diffraction limited @ 8keV

ERL emittance (0.015nm),
i.e., α =4400 nm^{-2}

Diffraction limited source: $2\pi\sigma'\sigma = \lambda/2$ or $\varepsilon = \lambda/4\pi$

Almost diffraction limited: $2\pi\sigma'\sigma \sim \lambda$ or $\varepsilon \sim \lambda/2\pi$

Cornell ERL: diffraction-limited source *E < 6.6 keV*
almost* diffraction-limited to *13 keV

ERL: Source Size and Pulse Length

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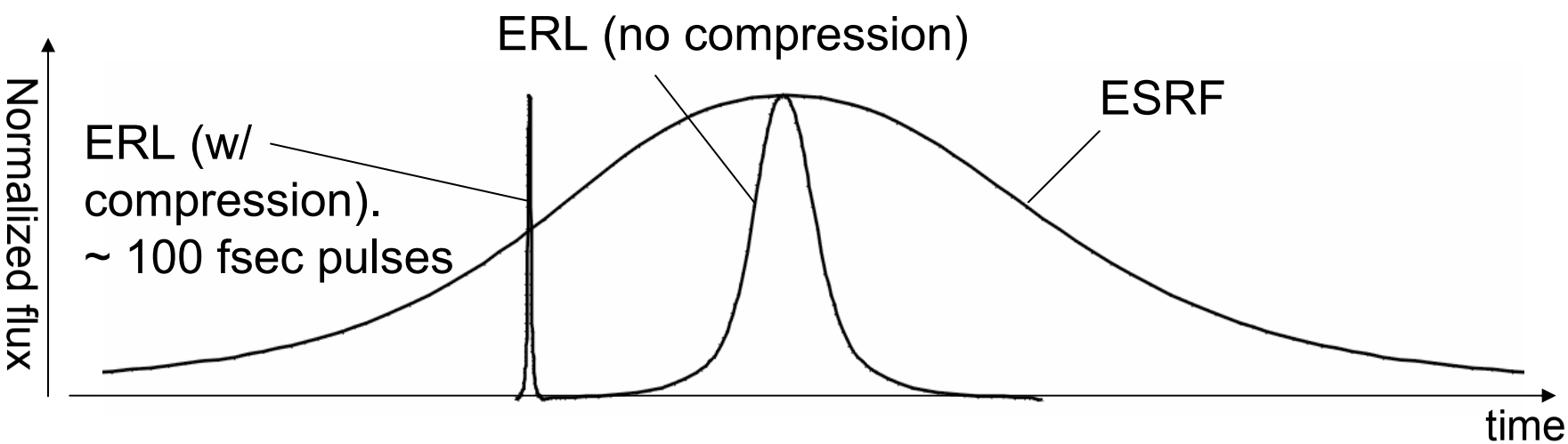
ESRF 6 GeV @ 200 mA

ε_x = 4 nm mrad
ε_y = 0.01 nm mrad

ERL 5 GeV @ 100 / 10 mA

$\varepsilon_x = \varepsilon_y$ = 0.2 / 0.02 nm mrad



ERL Science

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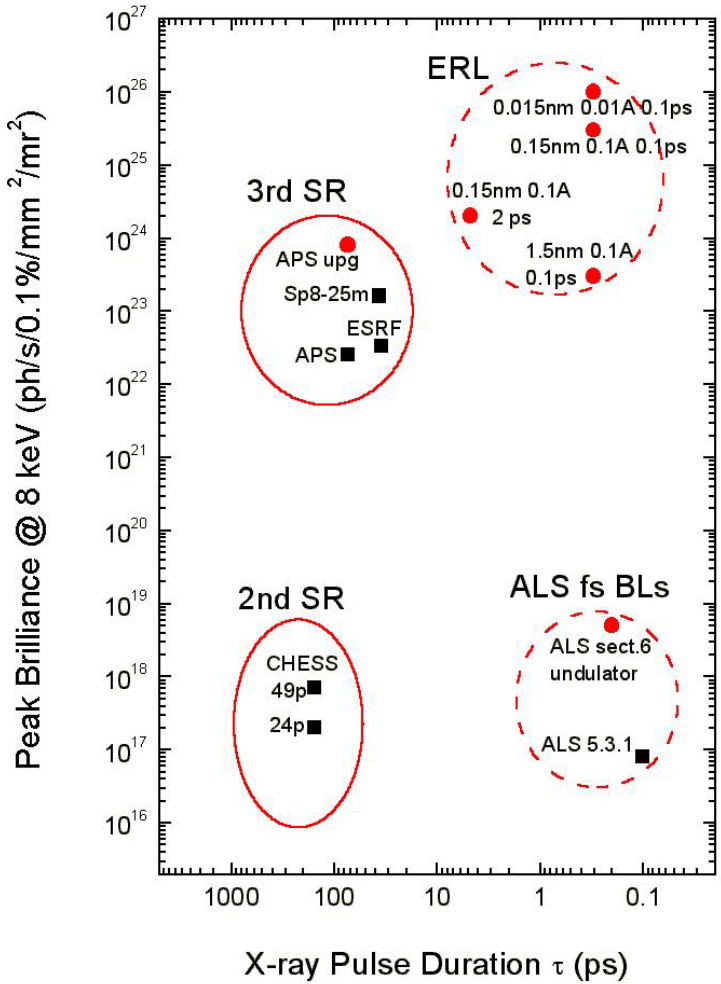
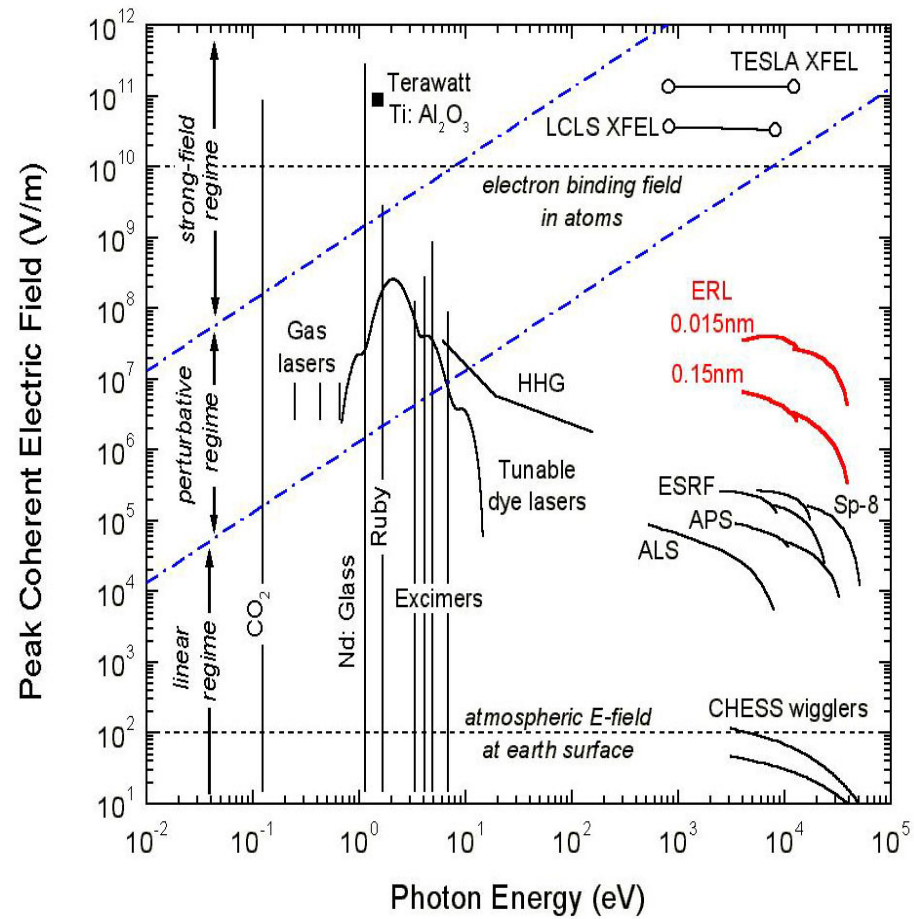
⇒ parameters in new regimes





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Source Size & Divergence

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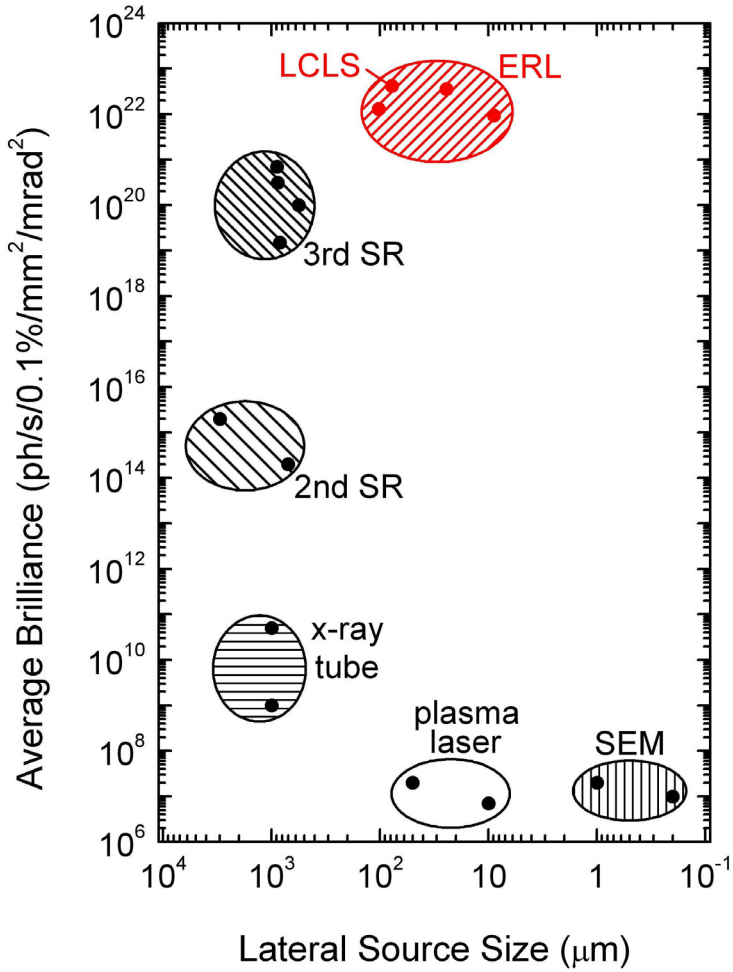
	Sigma x (μm)	Sigma x' (μrad)	Sigma y (μm)	Sigma y' (μrad)
ESRF Microfocus BL ID13	57	88.5	10.3	7.2
Advanced Photon Source	359	24	21	6.9
Energy Recovery Linac 100 mA, 25 m ID beta=4m, segmented	24.5	6.1	24.5	6.1
Energy Recovery Linac 10 mA, 2 m ID beta=1m	3.2	3.2	3.2	3.2

Brilliance vs. Source Size

CHESS & LEPP

⇒ parameters in new regimes



Basic Comparison of ERL, Storage Rings, XFEL

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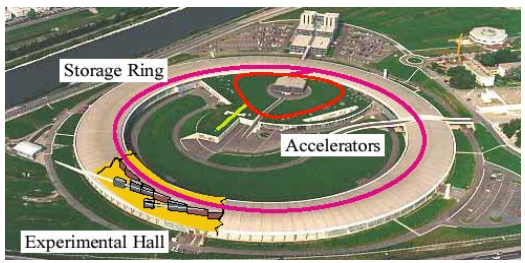
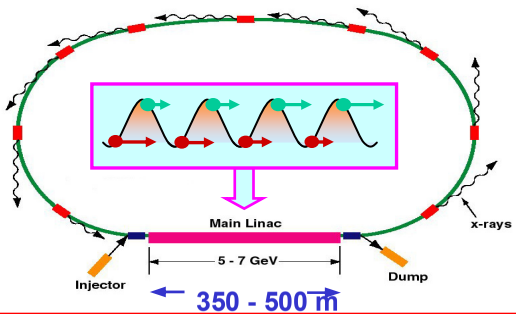
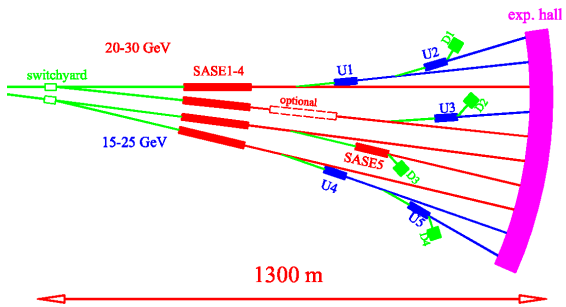
Storage Ring	ERL	XFEL
•Beam pwr dribbled in	•Beam pwr in one pass	•Beam pwr in one pass
•Low bunch charge	•Low/high bunch charge	•High bunch charge
•Multi-pass	•Single/few-passes	•Single-pass
•Energy stored in beam	•Energy stored in linac	•Energy not stored
•High rep rate	•High rep rate	•Low rep rate
•Many simul. beamlines	•Many simul. Beamlines	•One beamline/bunch
•Full x-ray pulse to ~ 30ps	•Full x-ray pulse to ~ 100 fs	•Full x-ray pulse to ~100 fs
•Little coherence	•Mostly transverse coherent	•Fully coherent
•Flat beams	•Round or flat beams	•Round beams
•Expts like storage ring	•Expts like storage ring	•Expts unlike storage ring



ESRF





Some Scientific Motivations:

Two Examples

First Application Example: X-ray Microscopy/Imaging/Microbeams

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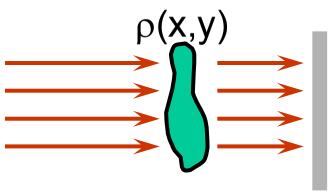
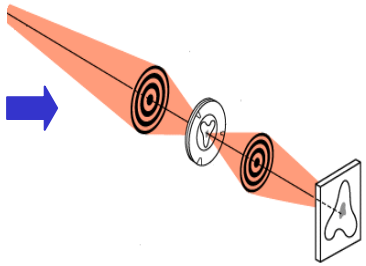
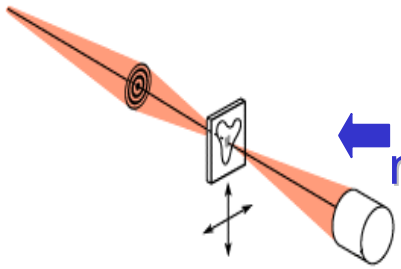


Direct imaging (radiography)

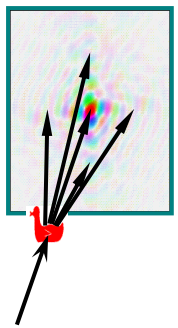
Transmission microscope (TXM)

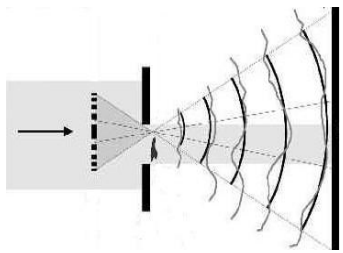




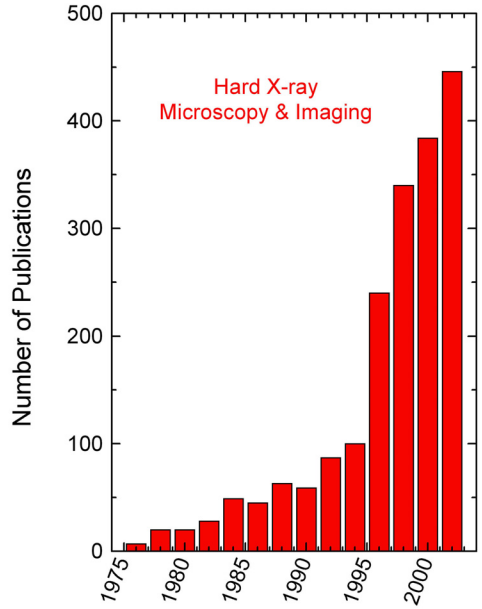
Scanning microscope (SXM)

Far-field diffraction





Holography



More on X-ray Microscopes

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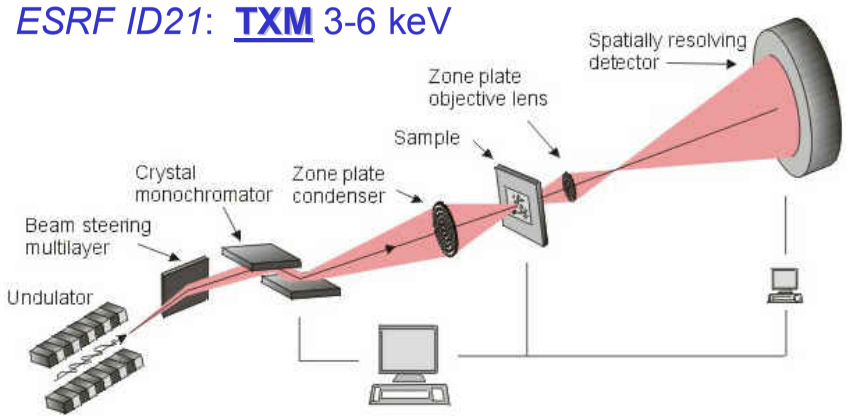
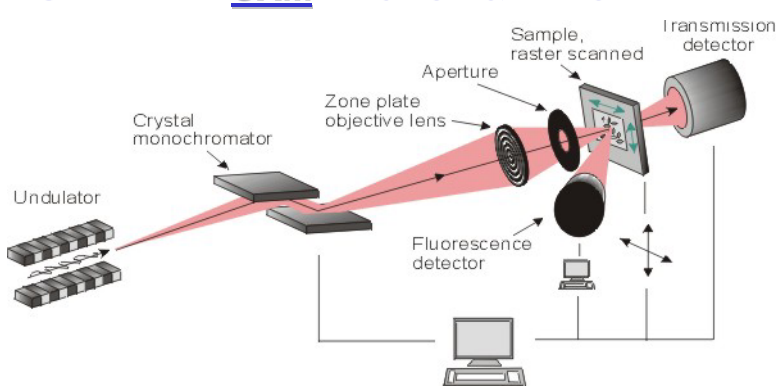
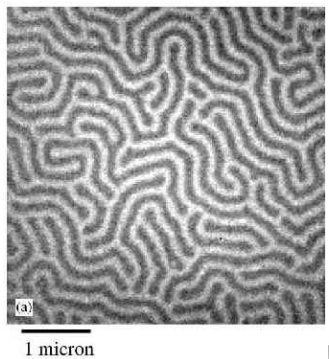
ESRF ID21: **TXM** 3-6 keV



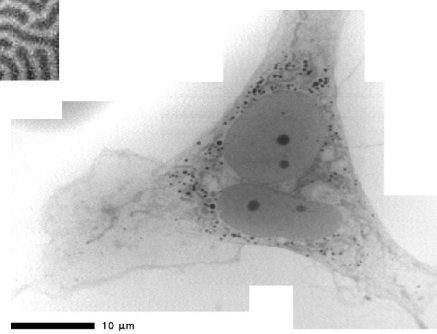
ESRF ID21: **SXM** 2-10 keV & < 2keV



- All types of materials are studied, from biological to magnetic
- Increasing number of SR imaging micro-scopes worldwide due to availability of
  => lens-like optics: e.g., zone plates, KB mirrors
  => high-brilliance & high-energy synchr. sources
- **Most are based on soft x-rays, only 3-4 go beyond 3 keV**



Denbeaux et al. (2001): magnet domains in Fe/Gd ALS XM-1, 0.7 keV XMCD



Jacobsen et al. (1996): wet chick embryo skin tissue NSLS X1 soft x-ray microscope

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Advantages of Hard X-ray Microscopy

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- **Much larger penetration depth,** important for naturally thick living specimens and materials science samples.
- **Larger depth of focus,** which is necessary for 3D tomography.
- **Access to high energy absorption edges** for fluorescence imaging and element mapping.
- **Increases opportunities for diffraction from buried crystals** in noncrystalline matrices, e.g., with nanocrystals.

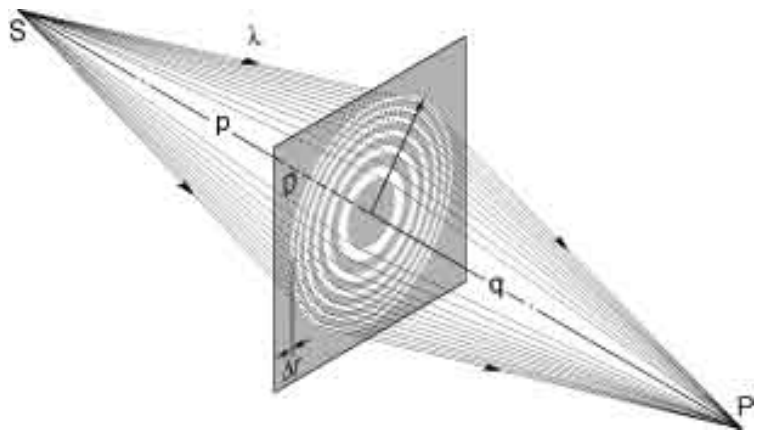
Why only a few hard x-ray microscopes ?

CHESS & LEPP

While all parts (source, optics, sample, detector, technique) need to work for success, frequently missing:

- High coherence sources

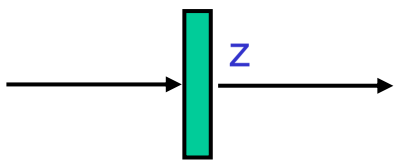
Coherence is frequently (but not always!) needed.
Coherence fraction ~ $\lambda^2/(\varepsilon_x\varepsilon_y)$.
=> Requires 100x smaller emittance product for 1keV => 10 keV



- High resolution focusing optics

Only recently has Fresnel zone-plate (FZP) achieved <100nm spatial resolution at 8 keV (Yun, 1999). Now it is 60nm (Yun, 2003).

X-ray Contrast



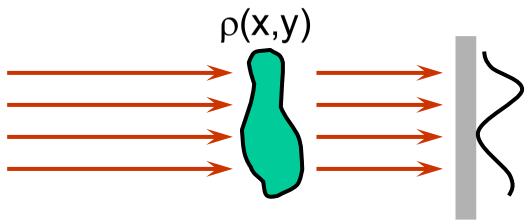
Refraction index: $n = 1 - \delta - i\beta$

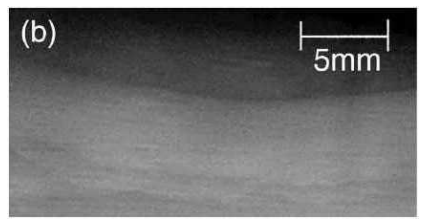
$$E(z) \sim E_0\, e^{-i2\pi(-\delta - i\beta)z/\lambda} \sim E_0\, e^{i2\pi\delta z/\lambda - 2\pi\beta z/\lambda}$$

$$I(z) \sim |E(z)|^2 \sim I_0\, e^{-4\pi\beta z/\lambda}$$

⇒ Absorption contrast:

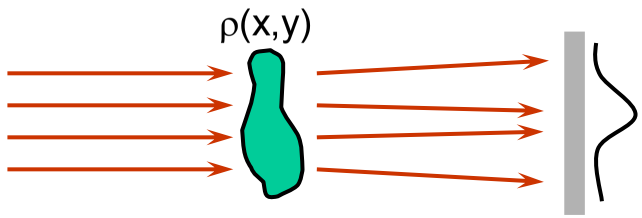
$\mu z = 4\pi\beta z/\lambda \sim \lambda^3$

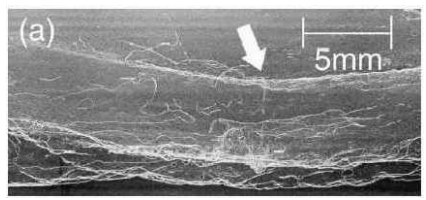




⇒ Phase contrast:

$\phi(z) = 2\pi\delta z/\lambda \sim \lambda$





Issues in Hard X-ray Microscopy
Contrast per Unit Dose

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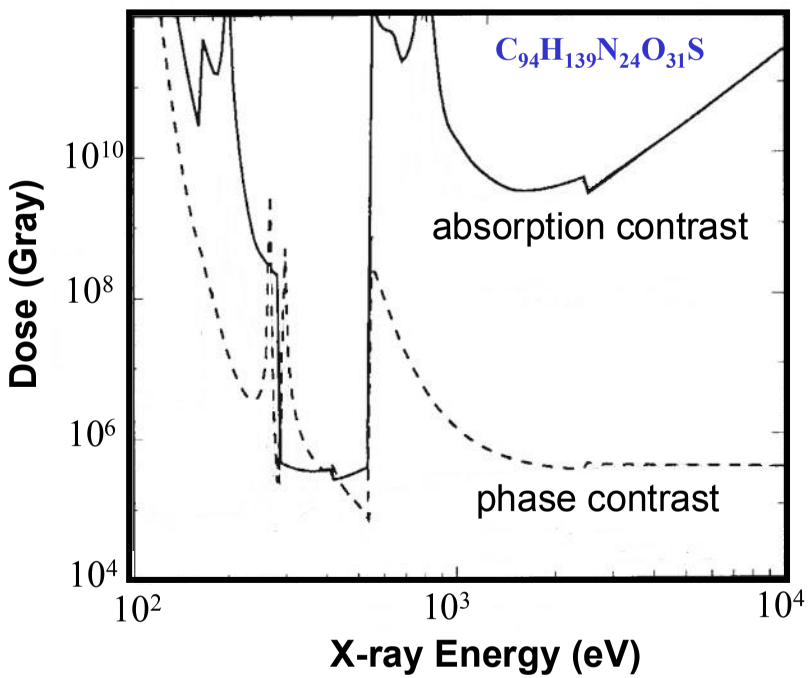
CHESS & LEPP

Very often challenging hard x-ray phase contrast imaging requires coherent beams

Coherence fraction ~ $\lambda^2/(\varepsilon_x\varepsilon_y)$.

ERL: 10^2-10^3x better emittance product than present hard x-ray sources

=> Better coherence @10 keV than @1 keV at ALS.



Kirz et al, Q. Rev. Biophys. ***28*** *(1995) 33*: Minimum dose for $(0.05\mu m)^3$ protein in $10\mu m$ thick ice.

Issues in Hard X-ray Microscopy
Optics

- Brightness theorem limits optical throughput, i.e., at best, the source size-divergence product is constant. => Smaller source is always better.

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Issues in Hard X-ray Microscopy
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- Brightness theorem limits optical throughput, i.e., at best, the source size-divergence product is constant. => Smaller source is always better.
- For 2-dimensional imaging, a round source generally allows better utilization of available photons.
- Milking the maximum performance from an ERL source will require development of better optics, but x-ray microprobes to 10 nm dimensions are likely possible.

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The world is made of materials that are granular on micrometer and submicrometer length scales

CHESS & LEPP

- A primary goal of materials science is to understand how properties (e.g., strength, failure modes, electronic properties) of solids (e.g., metals, ceramics, organics and composites) follow from atomic structure.
- Atomic structure is determined by analysis of bulk single crystals.
- However, extrapolation of properties from behavior of bulk single crystals fails to account for real materials properties.
- These failures highlight a need to understand microcrystalline structure, strain, and domain interactions at domain interfaces on relevant length scales. Many of these interfaces are buried and inaccessible by electron microscopy.

Differential-Aperture X-ray Microscopy (DAXM) (Thanks to Ben Larson et al.)

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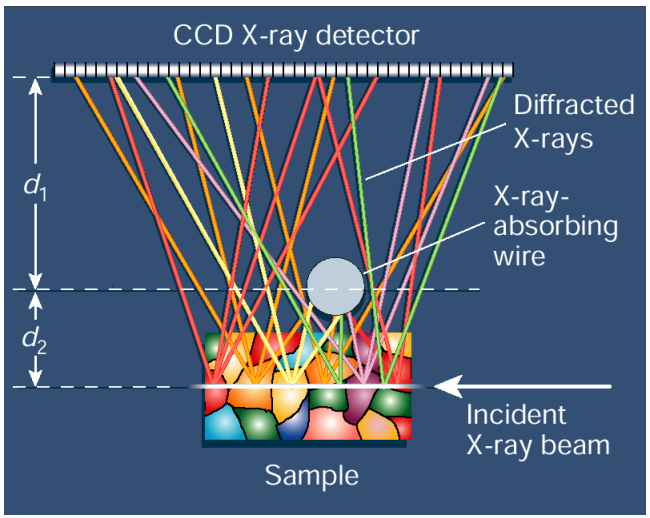
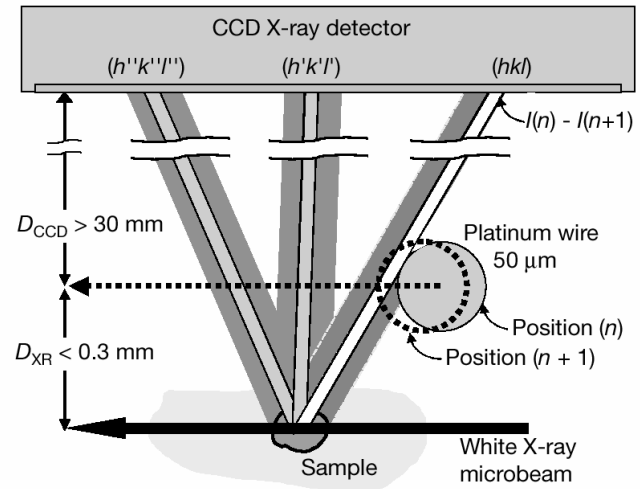
CHESS & LEPP

Cargill (intro to Larson), Nature, 2002





Larson, et al., Nature, 2002

"The availability of ... DAXM... provides a direct, - and previously missing - link between the actual microstructure and evolution in materials and the results of numerical simulations ...on mesoscopic length scales"

These experiments are microbeam flux limited. ERL would extend realm.

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Other ERL Materials Applications

CHESS & LEPP

Measure microstructure in the 3d bulk, probe (0.5 μm)**3

Measure stress/strain on individual grains

Study recrystallization and annealing

Fundamental plastic deformation investigations

Provide direct linkage with theory and simulation

ERL allows study of 1000-fold smaller volume than present and on time scales many orders of magnitude shorter. This vastly increases the range and types of materials that can be studied.

motivated by Larson, et al. *Nature* **415**, 2002, 844-845

Time-Resolved MicroSAXS of Macromolecular Solutions (Thanks to Lois Pollack)

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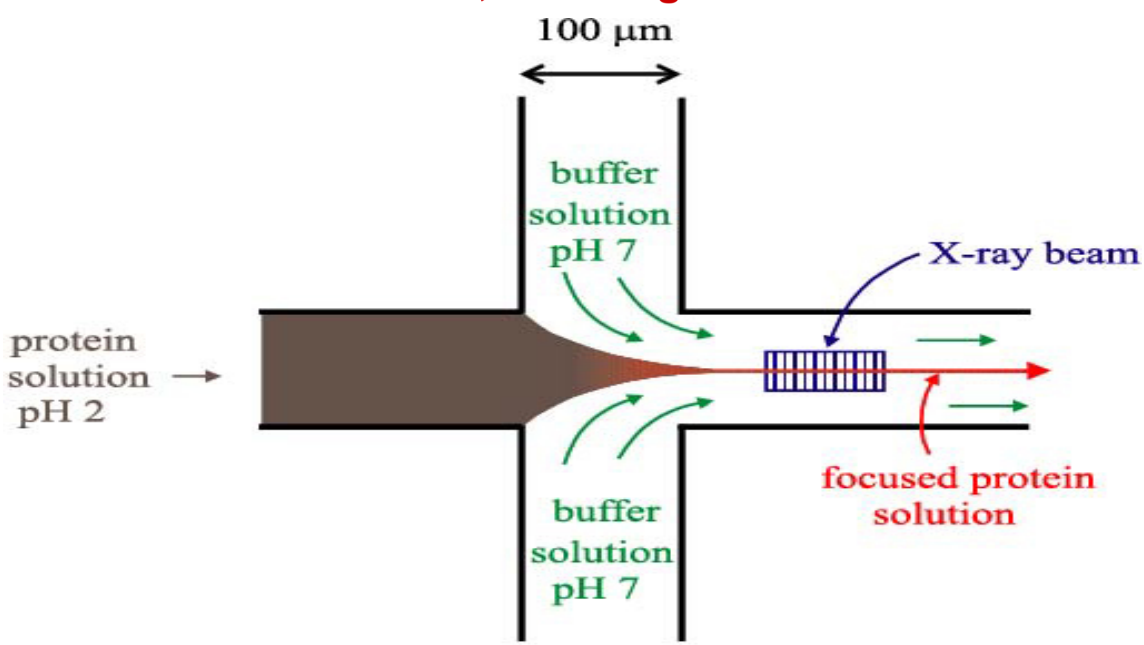
CHESS & LEPP

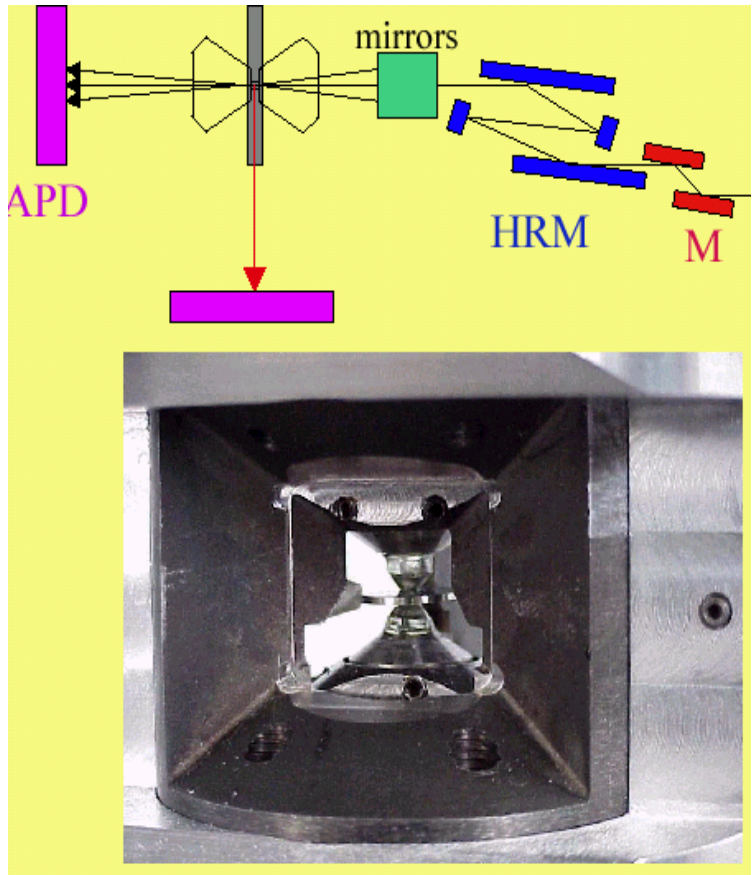
- Few probes of time-resolved structure of macromolecules in solution.
- Systems include: folding/unfolding of proteins & RNA; assembly of fibers; polymer collapse upon solvent changes; conformational changes upon ligand binding.
- Lithographically fabricated laminar-mixing flow cells have 10^{-6} to 10^{-3} sec.
- Radiation damage eliminated by flow.
- Systems probed in native water environment – biologically important.
- Data acquisition entirely limited by source brilliance. The ERL can extend feasible illuminated areas to submicron, resulting in microsecond time resolution.



High Pressure & Condensed Matter Research (Thanks to J. B. Parise, H.- K. Mao and R. Hemley)

CHESS & LEPP

- Most HP experiments are brightness-limited.
- Higher P → smaller samples.
- Peak-to-background critical.
- Time resolved experiments for plasticity, rheology measurements, phase transitions, etc. are especially photon starved.
- Extra ERL brilliance can open orders of magnitude new "specimen" space.



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High Pressure Science Areas Expanded by ERL

CHESS & LEPP

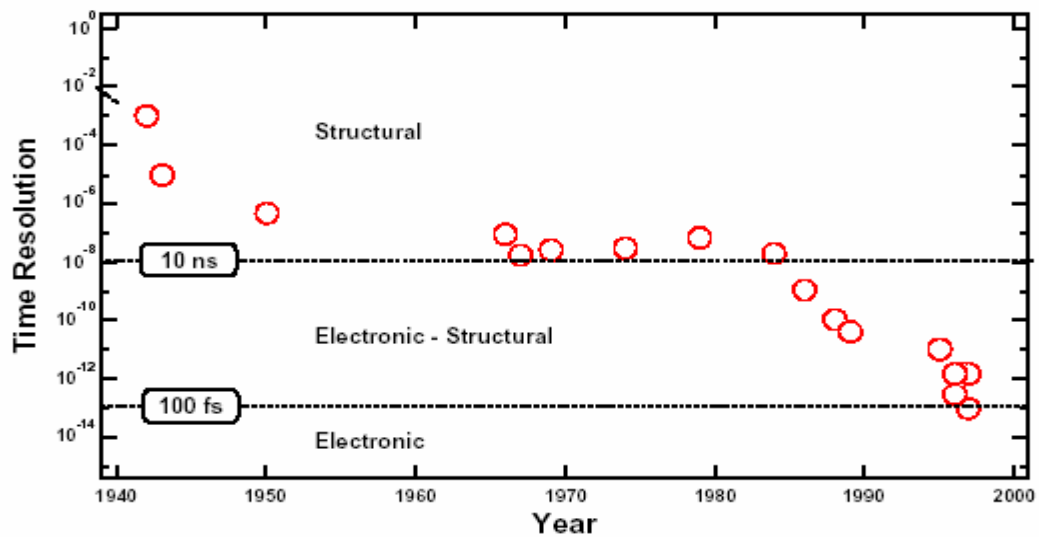
- Nature of dense hydrogen - *From cryogenic to brown dwarf conditions*
- Composition, elasticity, & thermal state of Earth's core - *Complex alloys; core P- T*
- Structures of complex hydrous phases - *Clathrates, molecular compounds, hydrous silicates*
- Supercritical fluids & liquids – *Structure, dynamics & 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, stress on magnetic properties - *From lo 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*

2nd Example: Ultrafast Structural Studies

Evolution of Ultrafast Hard X-ray Science

CHESS & LEPP

Important Sub-picosecond Threshold for Electronic Effects Reached in Mid-90's



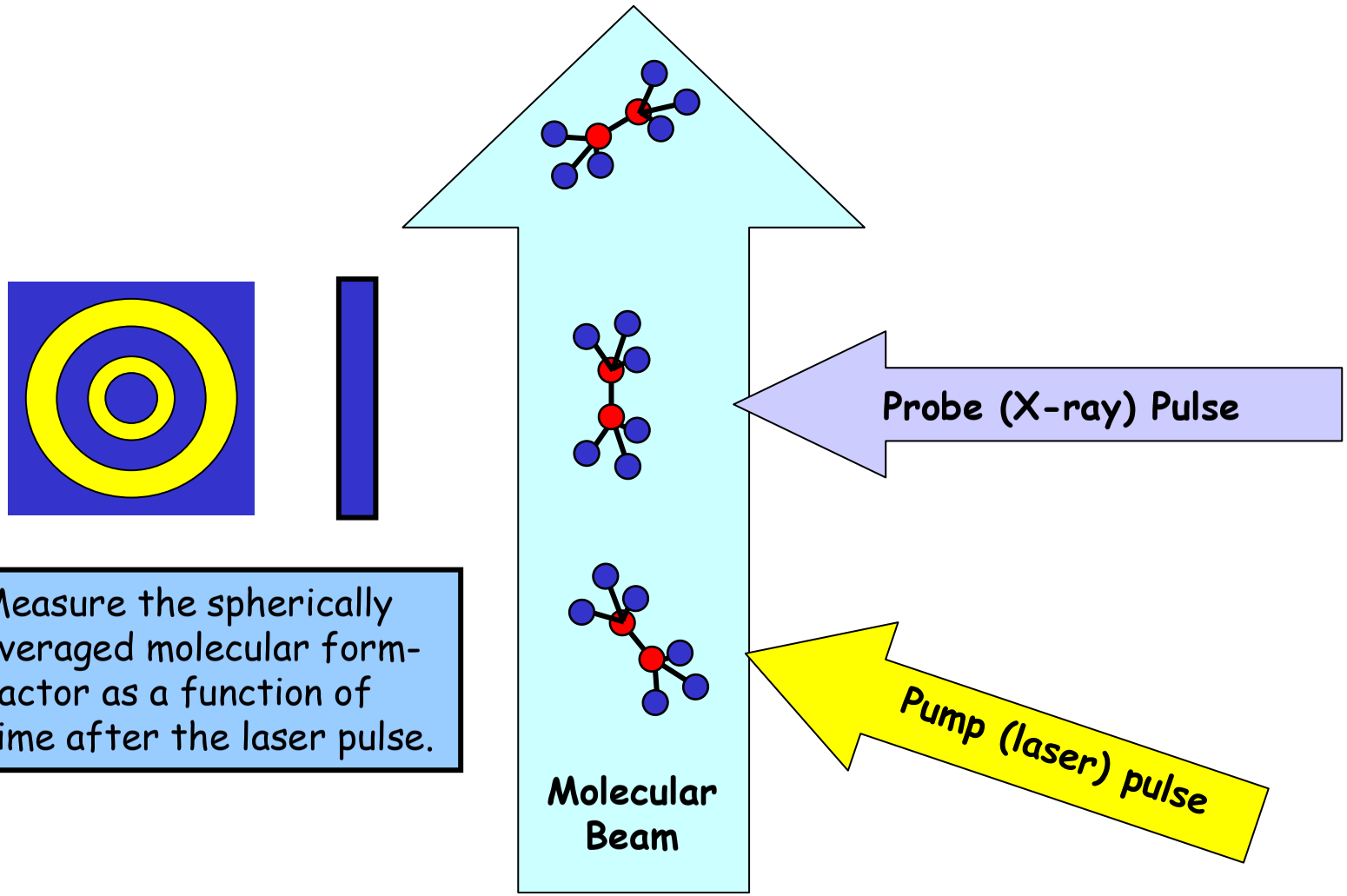
Structural Effects	Speed of Sound	~μm/ns
Electronic/Structural Effects	Electron-Phonon Interact.	<10 ps
Electronic Effects	Lattice Vib., Bonding	~100 fs

- Picosecond and Shorter X-Ray Pulses Open Important Areas of Fundamental Physics
- Present Picosecond X-Ray Pulses: Laser-Plasmas or Sliced Synchrotron Pulses
- Projected ERL Brilliance and Fluence Represent Significant Improvements

Energy Recovery Linac X-Ray Workshop

From Ben Larson, ERL Science Workshop

Pump/Probe Method

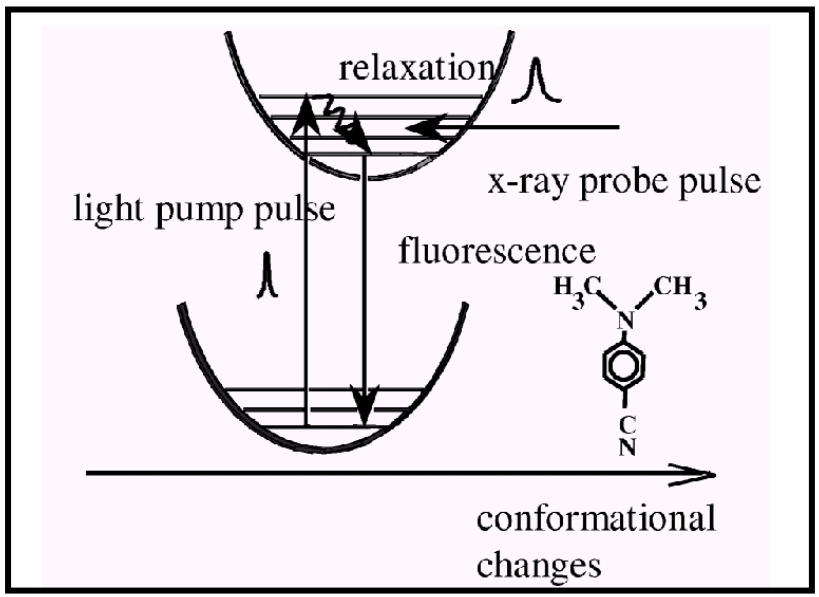


Measure the spherically averaged molecular form-factor as a function of time after the laser pulse.

Second Application Example: Ultrafast Chemistry

CHESS & LEPP

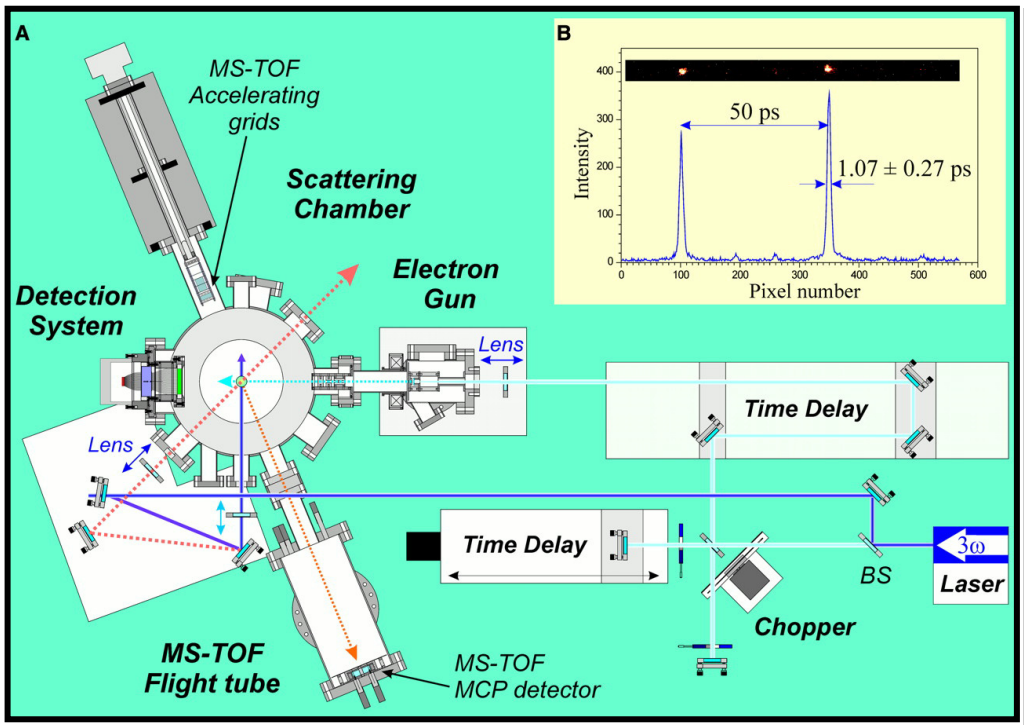
In many chemical areas, the scientific challenge is to understand the structural evolution of the "transition state(s)" intermediate between reactant and product species to supplement existing optical-pump/optical-probe spectroscopic info.

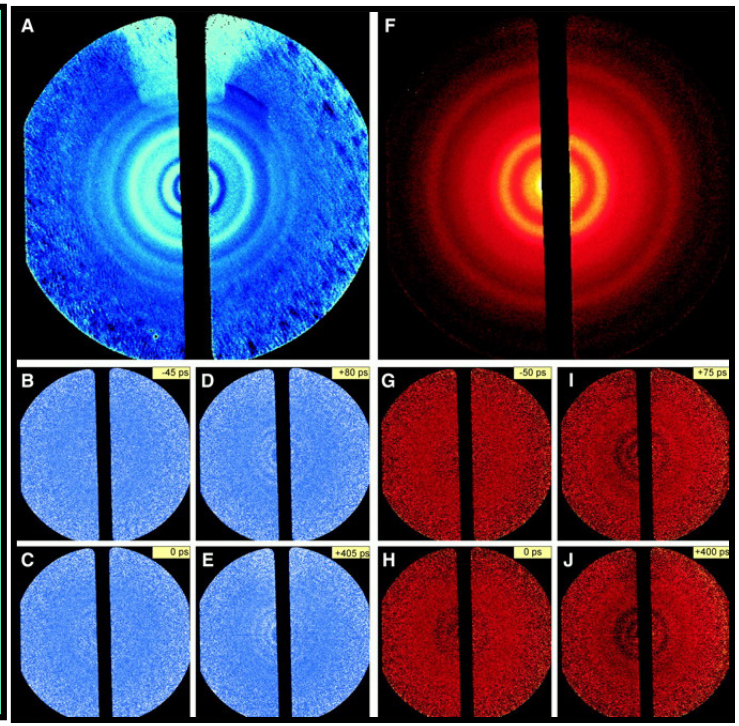


S. Techert, F. Schotte, and M. Wulff, Phys. Rev. Lett. **86**, 2030-2033 (2001).

Ultrafast Structure Studies

CHESS & LEPP





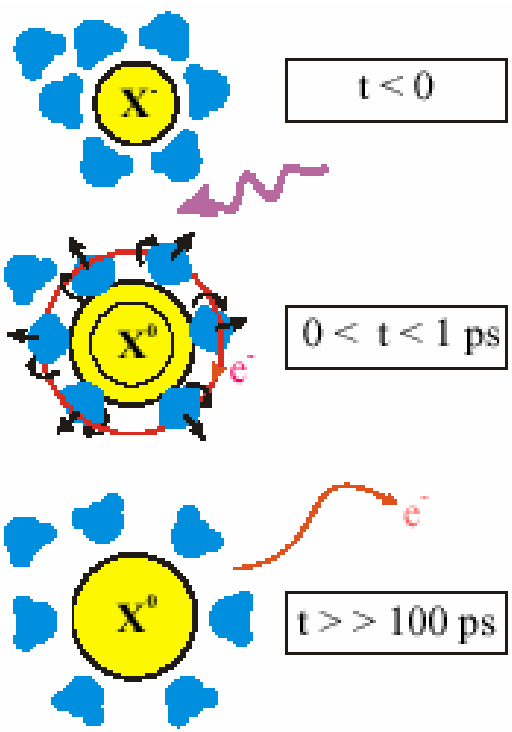
Caltech's Ultrafast Electron Diffraction (UED) apparatus.

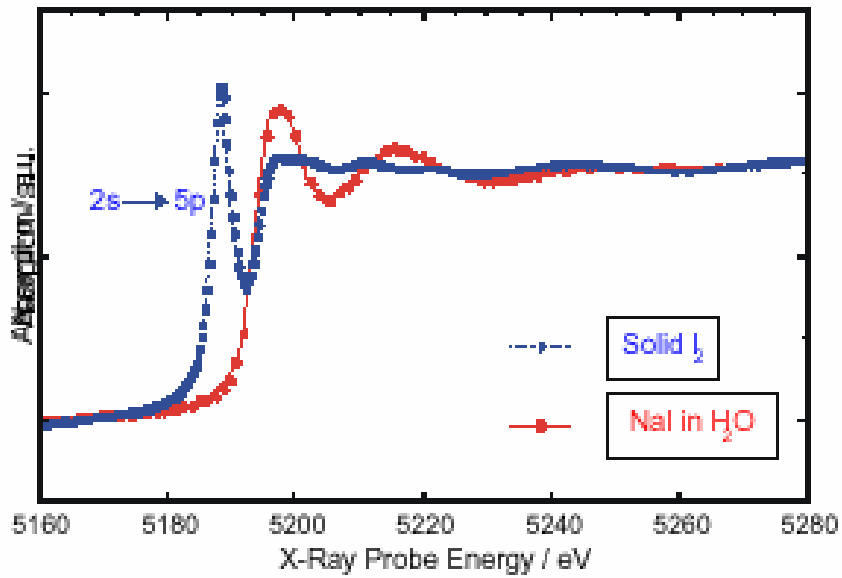
UED images of $C_2F_4I_2$ (blue) and 1,3-cyclohexadiene (red).

H. Ihee, V.A. Lobastov, U.M. Gomez, B.M. Goodson, R. Srinivasan, C.-Y. Ruan, and A. Zewail, Science **291**, 458-462 (2001).

These are psec expts. ERL would enable x-ray expts in <100 fsec range.

Another Example: Hydration Dynamics





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)

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Status of ERL Projects

CHESS & LEPP

ERL development intentions have been announced by

- Russia
- U.S. (several; Jlab, Cornell progressing)
- Japan (KEK progressing)
- England (4GLS progressing)
- Germany (several)

Many of these projects are for low-energy photons. The challenge will be hard x-rays at high flux and high brilliance. Of the progressing hard x-ray projects, Cornell and KEK seem to be the furthest along.

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But the Devil is in the details…

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What is needed to develop a hard x-ray high-flux, high-brilliance ERL as a practical, facility?

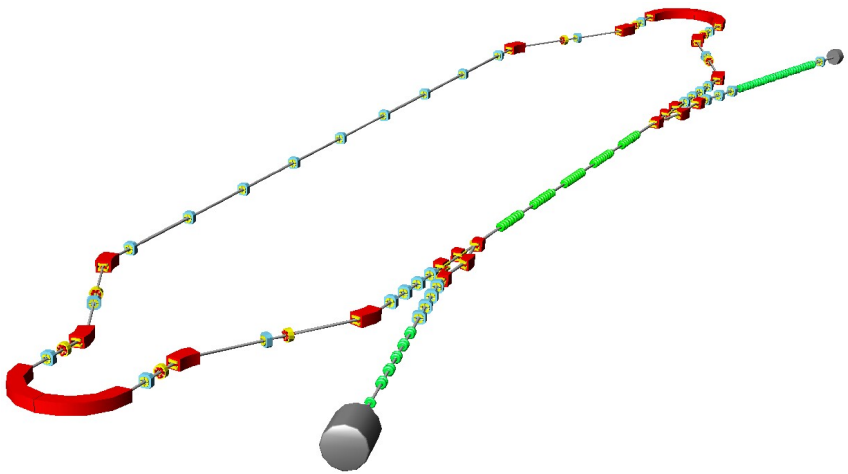
Prototyping is absolutely required to develop key aspects of the technology, followed by large-machine development. This needs appropriate funding, as well as expertise in:

1. Superconducting (SC) RF technology.
2. Accelerator & photoinjector physics.
3. Synchrotron x-ray science and technology.
4. Large-scale user facilities.

History of Cornell ERL Project

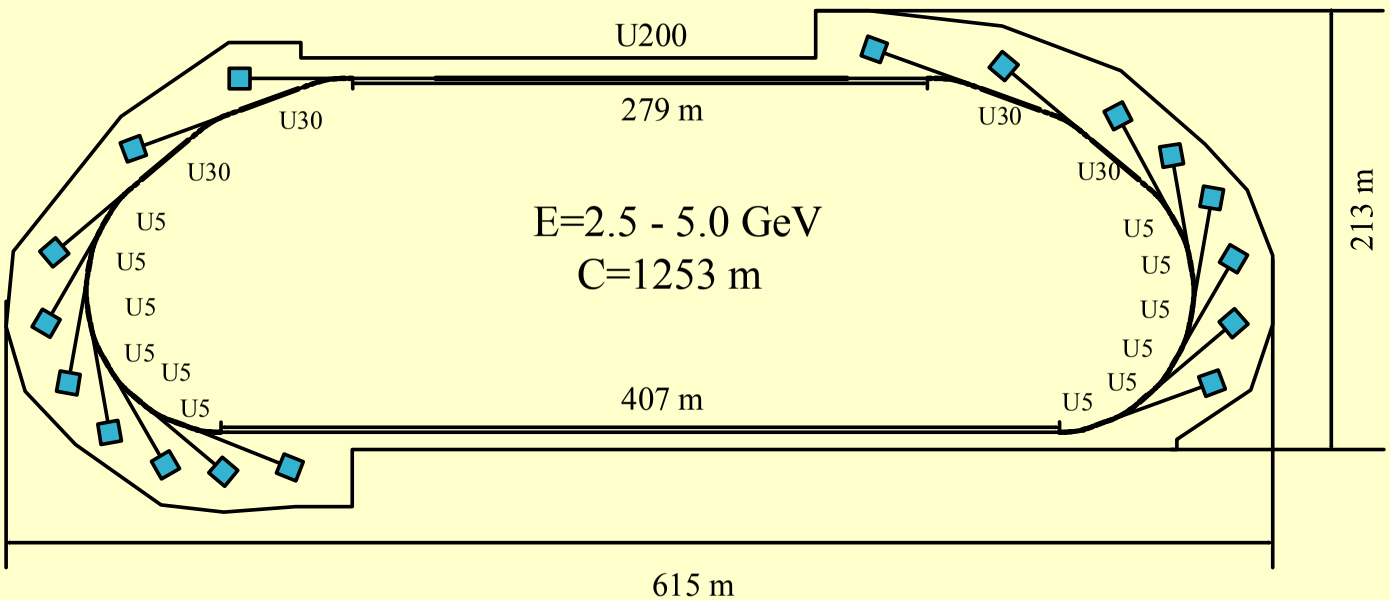
CHESS & LEPP

- Early 2000 ERL proposed to CHESS advisory panel
- July 2000 ERL White paper (http://erl.chess.cornell.edu)
- Summer 2000 Collaboration established w/Jlab
- Aug 2000 ERL machine physics workshop
- Dec 2000 ERL x-ray science workshop
  - Workshop conclusions: ERL is feasible, but best choices weren't obvious. Significant technical development needed I prototyping.
- Jan – July 2001 ERL Study performed. Defined Phases I & II. See http://erl.chess.cornell.edu/papers/ERL_Study.pdf
- July 2001 ERL Phase I proposed to NSF
- Mar 2002 ERL reviewed, site-visited by NSF PHY/DMR team. Funding strongly recommended.
- Initial funding from Cornell.
  Hoping for Oct. '03 NSF start.



Tentative ERL plan at KEK

- Beam energy : 2.5 GeV (phase I) - 5 GeV (phase II)
- Provide the 1st harmonic undulator radiation of 1 Å with an undulator period of 15 mm (present minimum).
- Insertion devices: 5 m × 12, 30 m × 4, 200 m × 1



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THREE REASONS TO DEVELOP ERL TECHNOLOGY

CHESS & LEPP

1. ERLs can do essentially everything now possible at the most advanced 3rd gen SR sources, thus meeting growth in demand for SR in a different way than for XFELs. XFELs are more likely to spur growth in wholly new areas.
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 circualr magnetic dichrosim studies
3. The inherent limits of ERLs are not yet known. Injector improvements may be expected, providing a relatively low cost upgrade pathway.

World-wide ERL plans are progressing.

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(Special thanks to Qun Shen for help w/ slides)

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M. Tigner	V. Veshcherevich	J. Welch (now SLAC)

Key: Red = Cornell; Blue = Jlab

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END