Cornell University
Laboratory for Elementary-Particle Physics

USPAS course on

Recirculated and Energy Recovered Linacs

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ERL as a X-ray Light Source

Jefferson Lab

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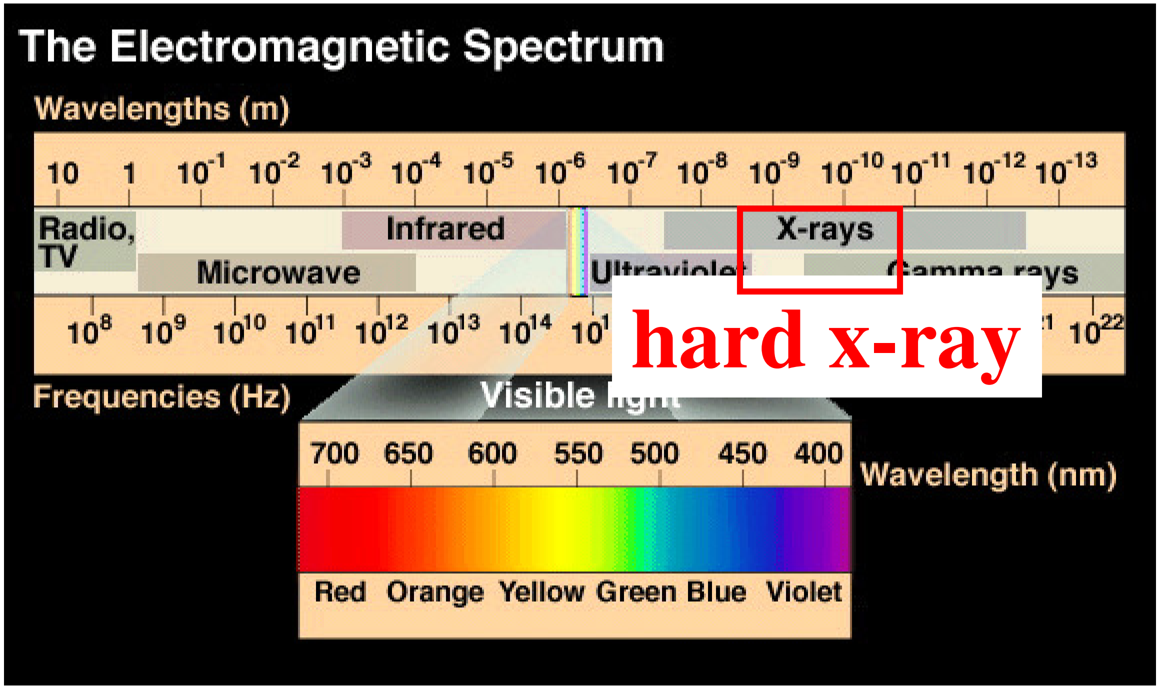
  - General motivation for a new light source
- Comparison with storage rings and XFELs
  - Storage ring basics
  - XFEL basics
- Science case examples
- Cornell ERL plan

Free e⁻ as medium



- Relativistic free electrons – the only medium for tunable light production in widest spectral range
- Hard x-ray range is the subject of this talk

?

ERL light source idea

Third generation light sources are storage ring based facilities optimized for production of high brilliance x-rays through spontaneous synchrotron radiation. The technology is mature, and while some improvement in the future is likely, one ought to ask whether an alternative approach exists.

Two orthogonal ideas (both linac based) are XFEL and ERL. XFEL will not be spontaneous synchrotron radiation source, but will deliver GW peak powers of transversely coherent radiation at very low duty factor. The source parameters are very interesting and at the same time very different from any existing light source.

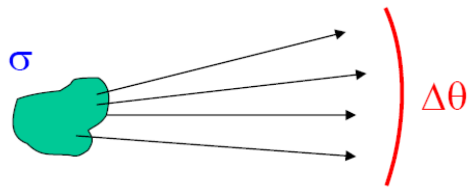
ERL aspires to do better what storage rings are very good at: to provide radiation in quasi-continuous fashion with superior brilliance, monochromaticity and shorter pulses.

X-ray brightness

Brilliance / Spectral Brightness

$$\frac{\text{FLUX OF PHOTONS IN UNIT SPECTRAL RANGE}}{\text{(SOURCE AREA) X (BEAM DIVERGENCE)}}$$

Units: Photons/s/mm²/mrad²/0.1% bandwidth



$$B = \frac{\Phi}{\sigma\, \Delta\theta_h\, \Delta\theta_v}$$

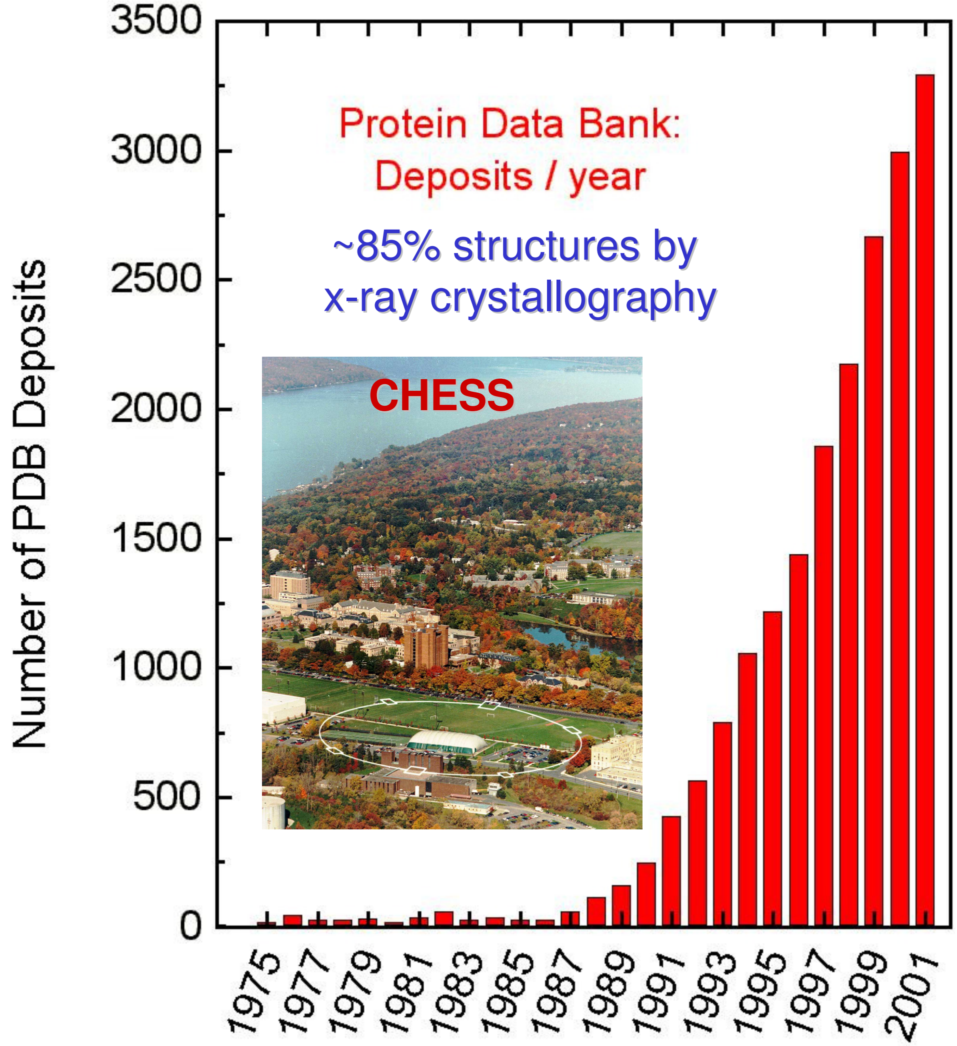
- **Average brightness:** measure of transversely coherent flux

$$F_c = B_{avg}\left(\frac{\lambda}{2}\right)^2$$

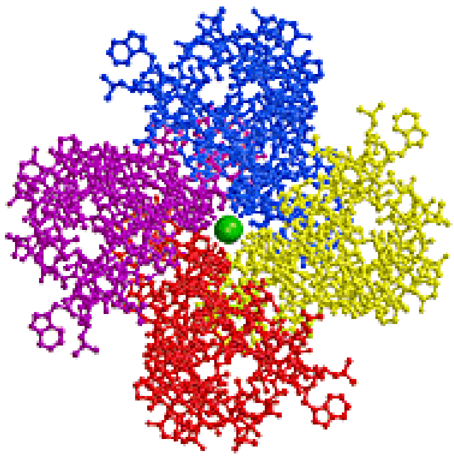
- **Peak brightness:** proportional to the number of photons per coherence volume in 6D phase space ≡ the photon degeneracy

$$\Delta_c = B_{peak}\left(\frac{\lambda}{2}\right)^3 \frac{\Delta\lambda}{\lambda}\frac{1}{c}$$

Demand for X-rays



Ion channel protein

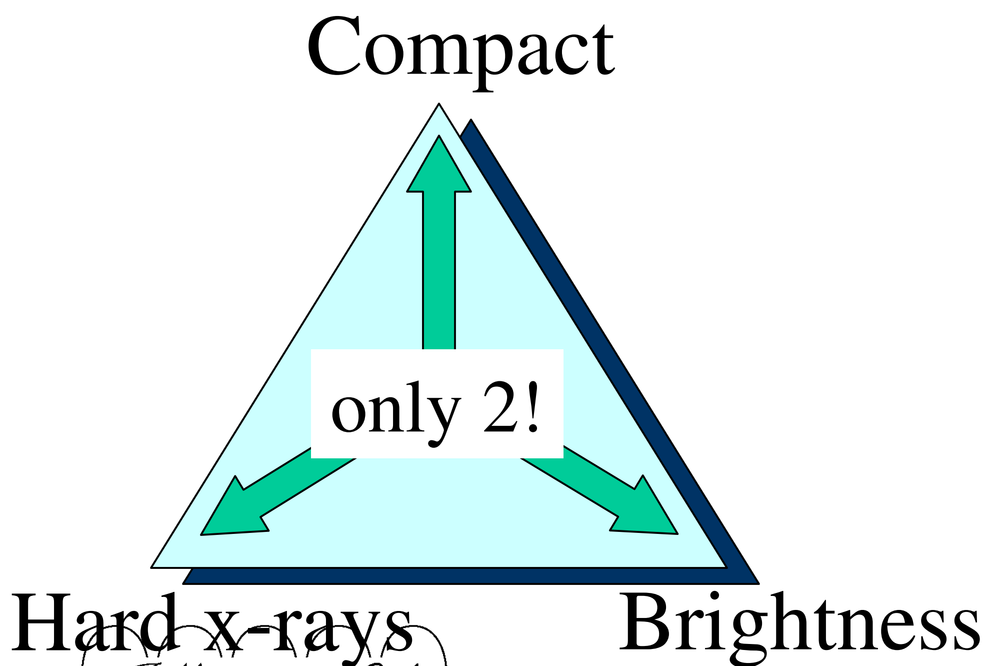


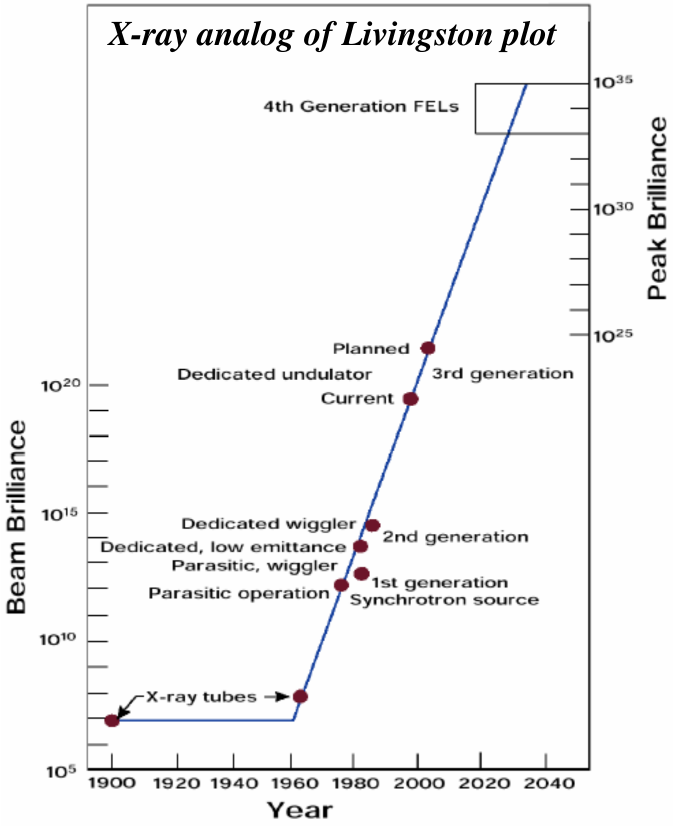
2003 Nobel Prize
in Chemistry:

Roderick MacKinnon
(Rockefeller Univ.)
1st K^+ channel structure
by x-ray crystallography
based on CHESS data (1998)

Three frontiers in source dev.

- Avg. brightness
- Short pulses (< ps) & peak brightness
- Compactness



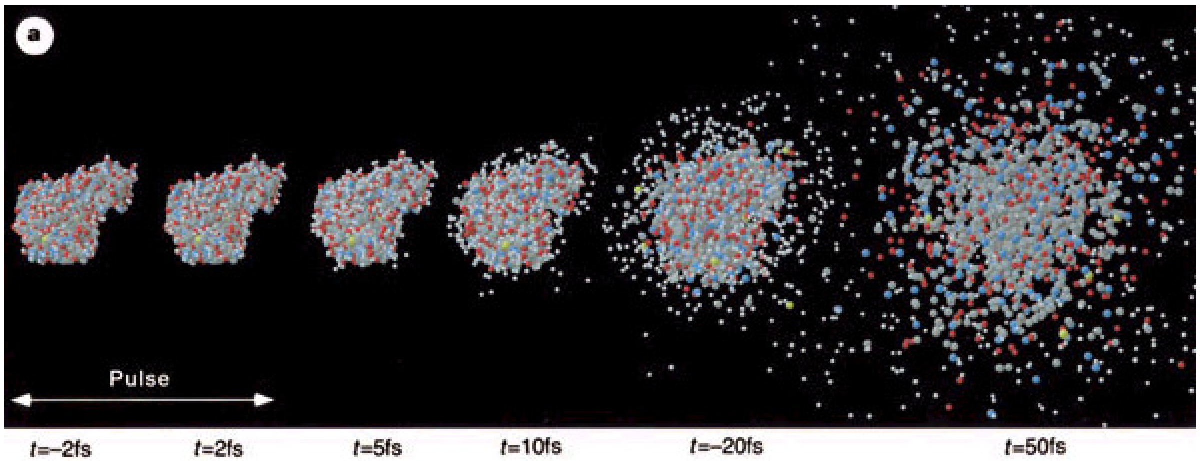


Light sources worldwide

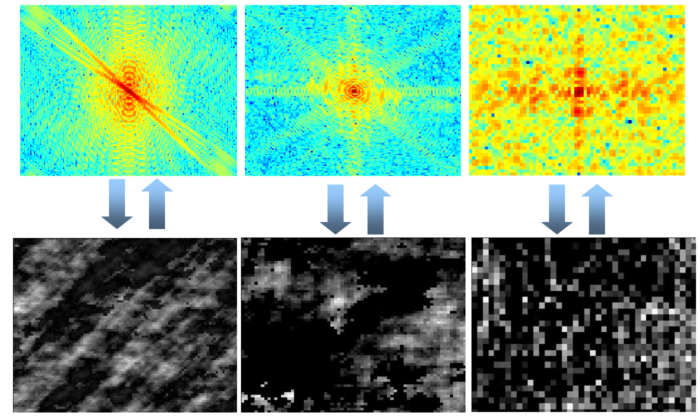
- About 70 light sources worldwide based on **storage ring** technology (**VUV to hard X-rays**), new ones are being built / designed
- 22 **FELs** operational, some as scientific research instruments (**far IR to VUV**)
- 3 **XFELs** in construction / committed to, plus half a dozen in CDR or earlier stages (**soft to hard X-rays**)
- 3 labs seriously consider building **ERL** as a **hard X-ray** light source

Exp1: ‘explosive’ proteins

R. Neutze, et al., *Nature*, **406**, 752



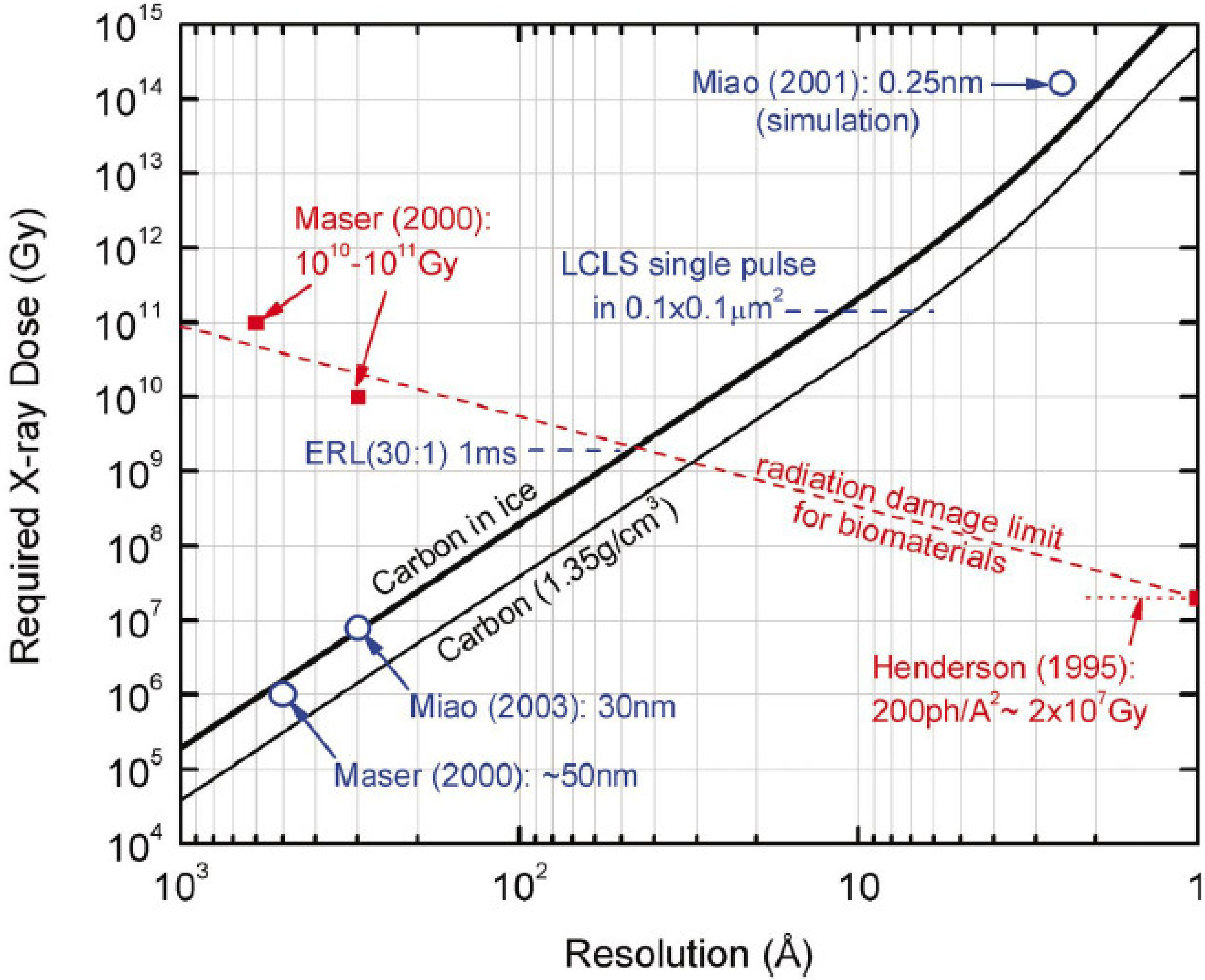
Fienup’s algorithm



Briefly: calculations were done for T4 lysozyme (diameter 32 Å, N_C ~ 1000);
flux 4×10^6 X-rays/Å^2 with ~ 2000 primary ionization events;
elastically scattered ~ 200 photons.
If pulse is sufficiently short (<10 fs), 5×5×5 lysozyme nanocrystal will scatter to <2Å resolution.

Key feature: sufficiently short X-ray pulse can beat Henderson’s limit of radiation damage (200 x-ray photons /A^2)

Radiation damage: biomaterials

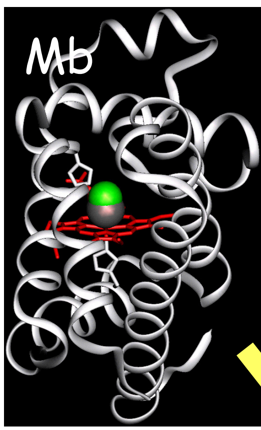


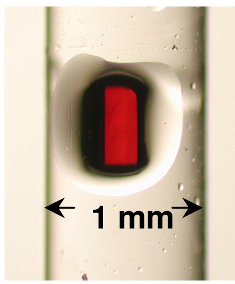
Shen, Bazarov, Thibault, J. Sync. Rad., Vol. 11 (2004) 432

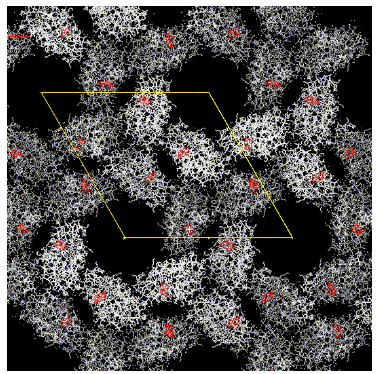
Exp2: fs chem. reaction movie

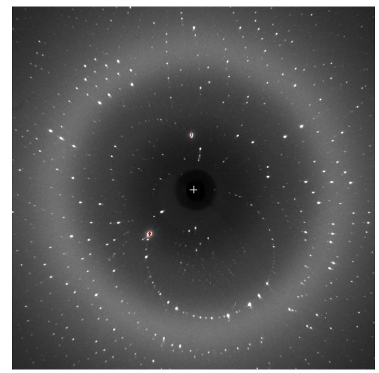
Broad class of pump-probe experiments providing structural (core e⁻'s) conformational changes in the initial stages (mol. vibrational timescale 10's fs) of photo-induced reactions

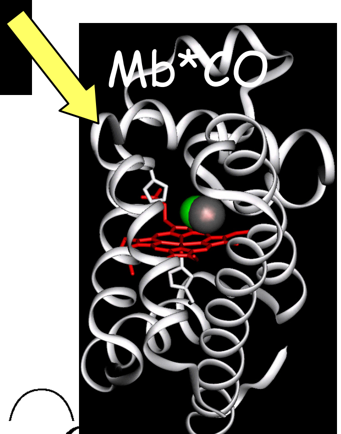
Time-resolved Laue Crystallography (Phil Anfinrud)

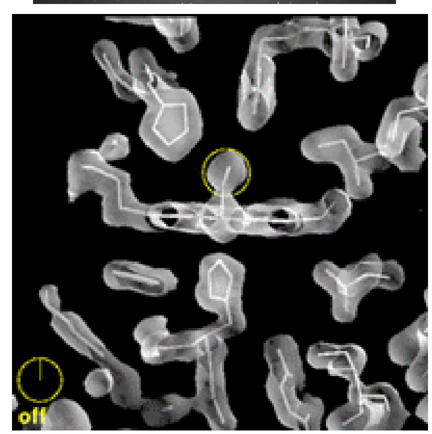






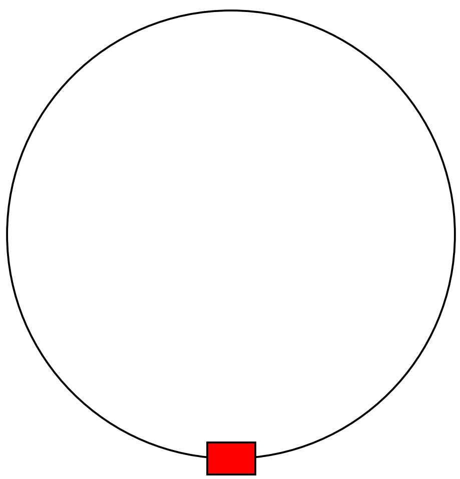






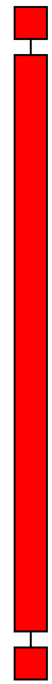
SR/XFEL/ERL

SR



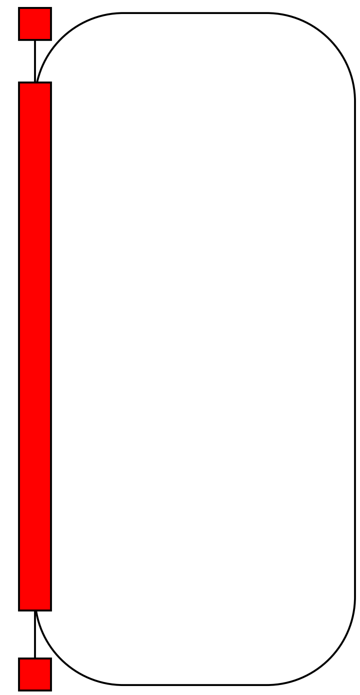
- efficient
- avg. brightness
- many beamlines
- workhorse technology

XFEL



- peak brightness
- short pulse
- few beamlines
- new user-base

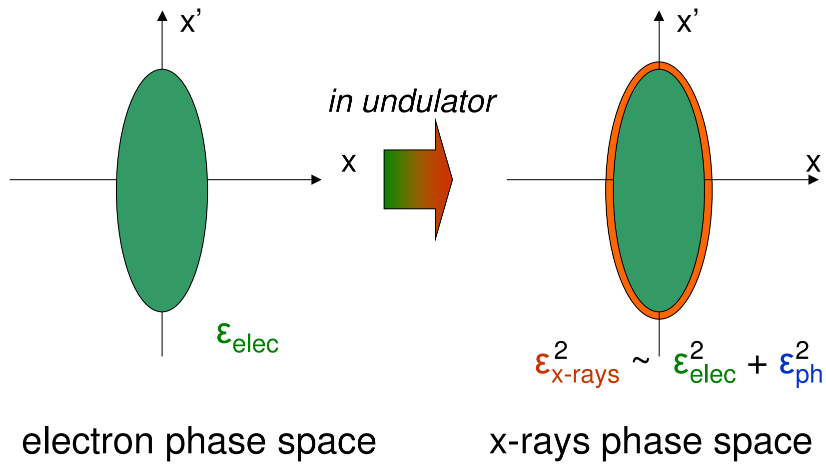
ERL



- avg. brightness
- short pulse
- many beamlines
- existing user-base

Diffraction limited e-beam

- In properly tuned undulator x-ray phase space is convolution of e-beam with diff. limit

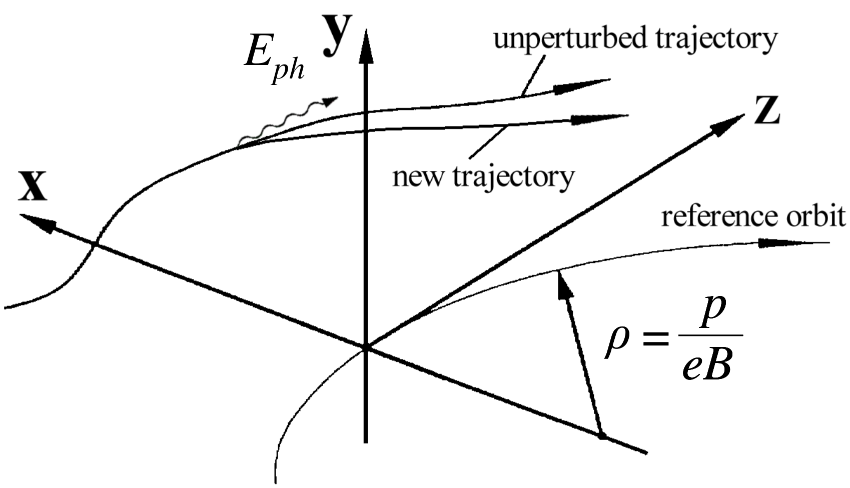


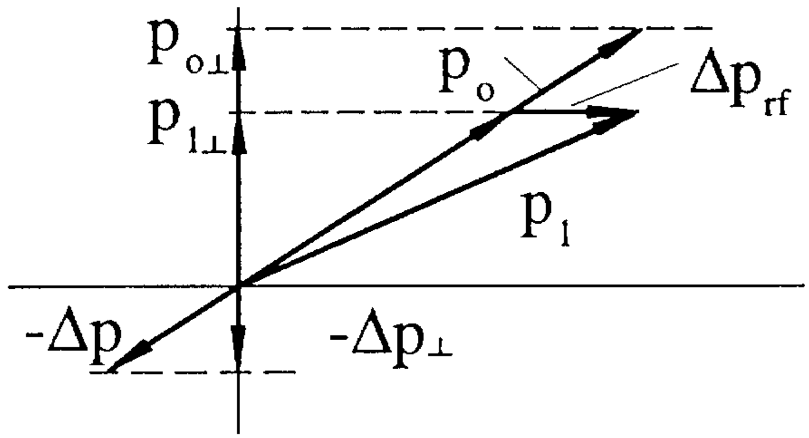
- **Goal**: for 1 Angstrom → $\varepsilon_x \sim \lambda/4\pi = 8$ pm geometric, or $\varepsilon_{nx} = 0.08$ μm if energy is 5GeV

- E.g. best storage ring performance as of today: $\varepsilon_x / \varepsilon_y = 3000 / 15$ pm

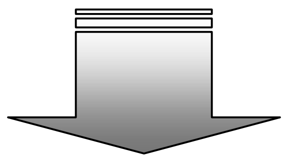
Equilibrium

Quantum Excitation **vs.** Radiative Damping





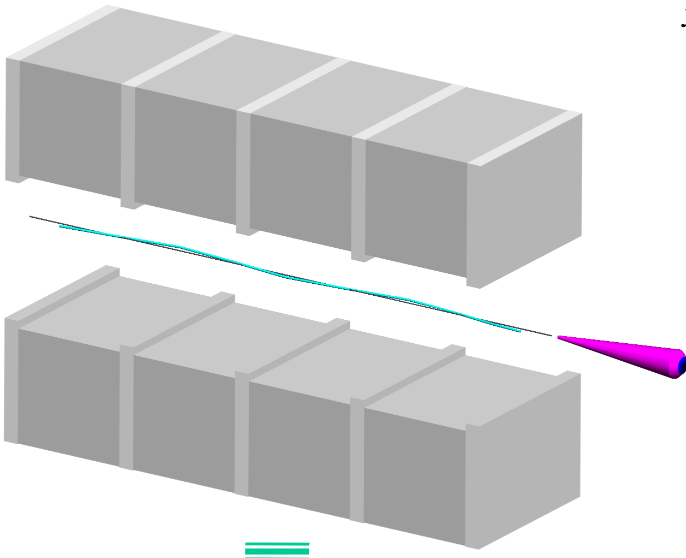
$$\frac{d\sigma_E^2}{dt} \sim \dot{N}_{ph} E_{ph}^2$$



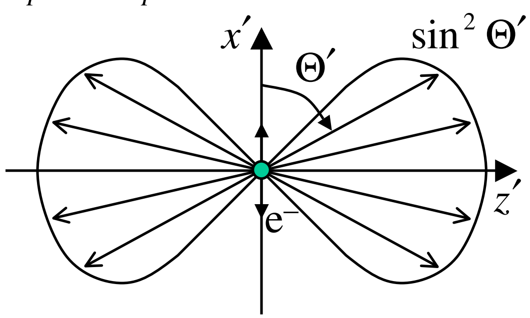
Emittance (hor.), Energy Spread, Bunch Length

Tighter focusing (higher tune) → stronger 6-poles for chromaticity correction → smaller dynamic aperture & lifetime

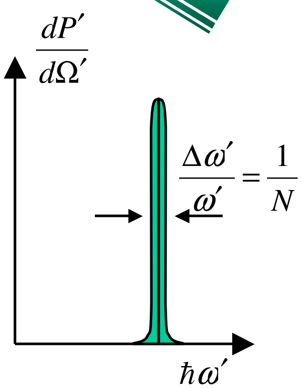
Basics of sync. rad. production

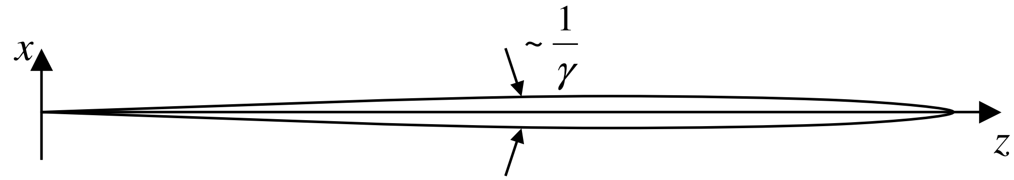


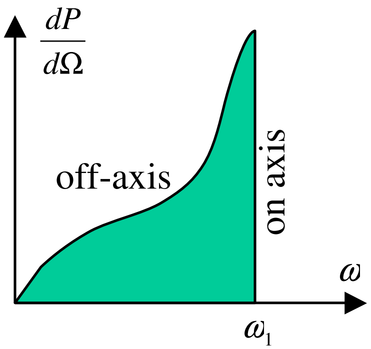
$\lambda_p' = \lambda_p / \bar{\gamma}$



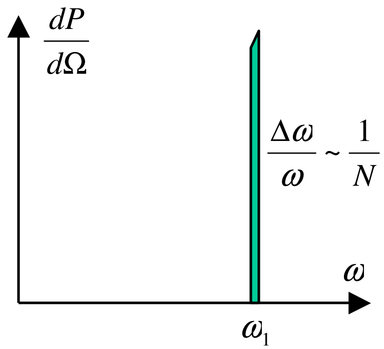
in e⁻ frame







back to lab frame

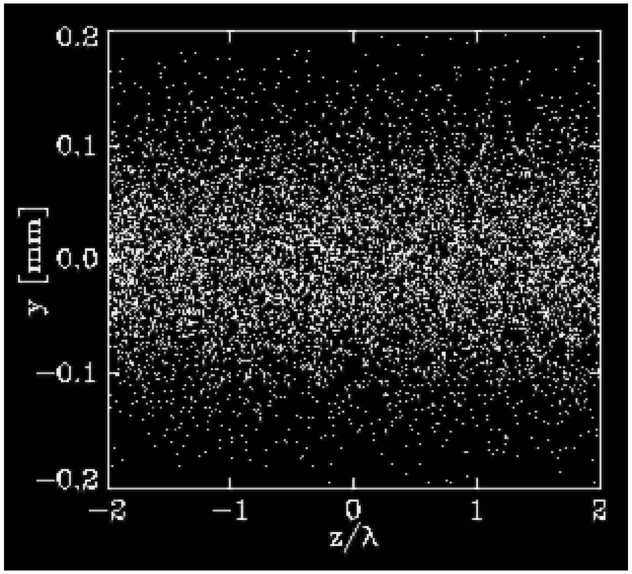


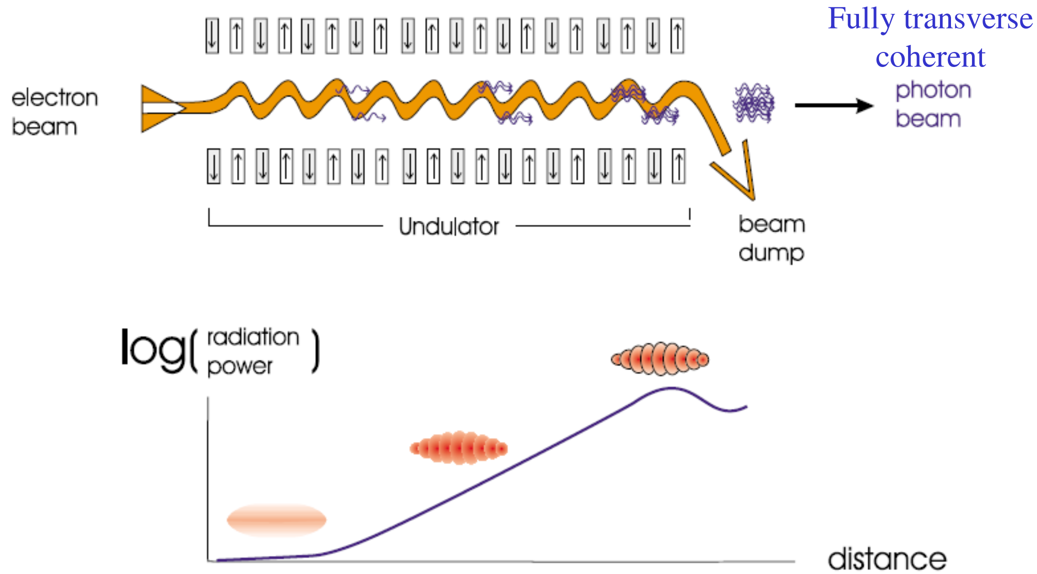
after pin-hole aperture

$$\lambda_n = \frac{\lambda_p}{2\gamma^2 n}\left(1 + \tfrac{1}{2}K^2 + \gamma^2\theta^2\right)$$

$$\frac{\Delta\lambda}{\lambda_n} \sim \frac{1}{nN_p}$$ (for fixed θ only!)

XFEL





Prerequisites for e⁻-bunch:

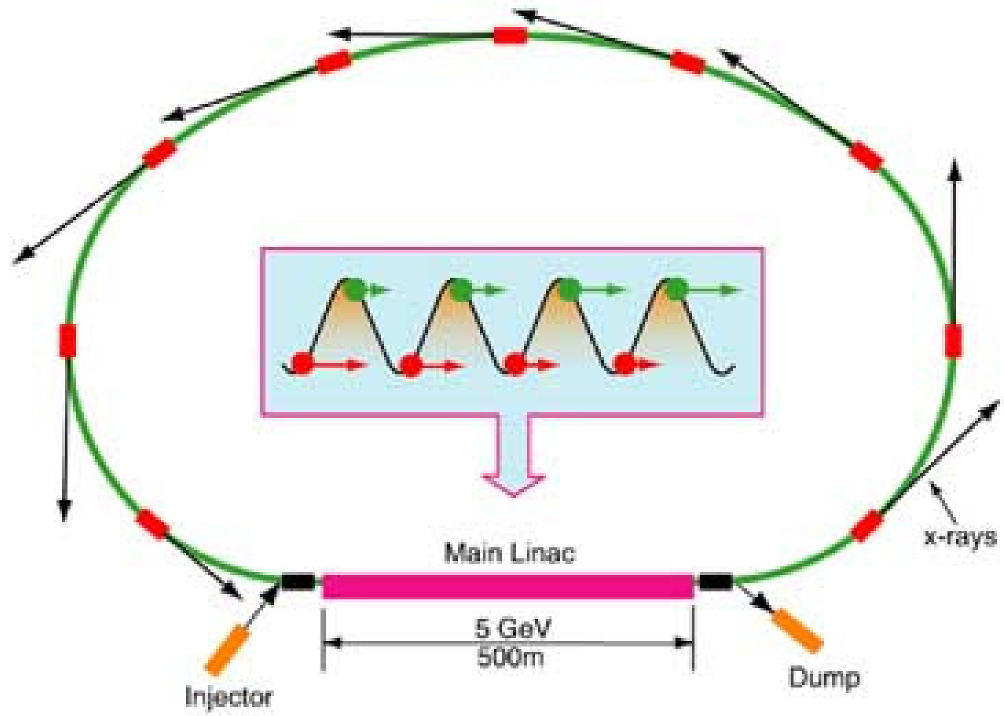
diffraction-limited emittance

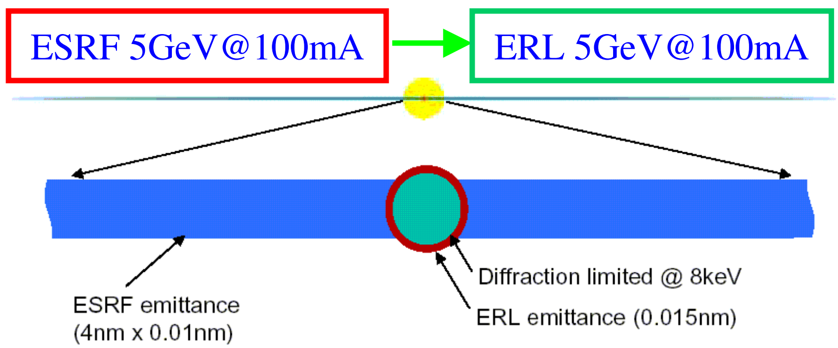
peak current 3-5 kA

energy spread 10^{-4}

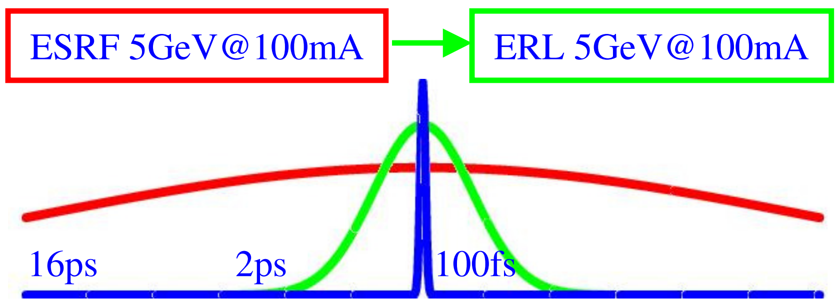
Intense relativistic electron bunch becomes effective gain medium (e.g. use seed / amplifier setup)

ERL promise





Much smaller (×100) horizontal emittance



Much shorter (×100) pulses

Source-limited: ERL vs. future SR

- Brightness figure of merit (FOM) $\frac{I}{(\varepsilon_x + \lambda/4\pi)(\varepsilon_y + \lambda/4\pi)}$ for 1Å

Light source	I (A)	ε_x (nm-rad)	ε_y (nm-rad)	FOM (A/nm^2/rad^2)
ESRF	0.2	3.7	0.010	3.0
Petra-III	0.1	1.0	0.010	5.5
NSLS-II*	0.5	1.54	0.008	20.24
UHXS(ESRF)	0.5	0.2	0.005	185.6

- 5 GeV ERL to achieve the same brightness per m of ID as Petra-III / NSLS-II / UHXS(ESRF) needs **1.3 / 0.6 / 0.15 μm** rms **normalized** emittance for **80 pC** bunch (0.1 A average current at 1.3 GHz bunch rep rate) assuming no emittance degradation downstream
- Comparison: ILC norm. emit. $\sqrt{\varepsilon_{nx}\varepsilon_{ny}}$ = **0.6 μm** for **3.2 nC**

* without use of damping wigglers

Cornell plans