Performance Metrics of Future Light Sources

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Science and Technology of Future Light Sources

A White Paper

Report prepared by scientists from ANL, BNL, LBNL and SLAC. The coordinating team consisted of Uwe Bergmann, John Corlett, Steve Dierker, Roger Falcone, John Galayda, Murray Gibson, Jerry Hastings, Bob Hettel, John Hill, Zahid Hussain, Chi-Chang Kao, Janos Kirz, Gabrielle Long, Bill McCurdy, Tor Raubenheimer, Fernando Sannibale, John Seeman, Z.-X. Shen, Gopal Shenoy, Bob Schoenlein, Qun Shen, Brian Stephenson, Joachim Stöhr, and Alexander Zholents. Other contributors are listed at the end of the document.

http://www-ssrl.slac.stanford.edu/aboutssrl/documents/future-x-rays-09.pdf

Argonne National Laboratory

Brookhaven National Laboratory

Lawrence Berkeley National Laboratory

SLAC National Accelerator Laboratory

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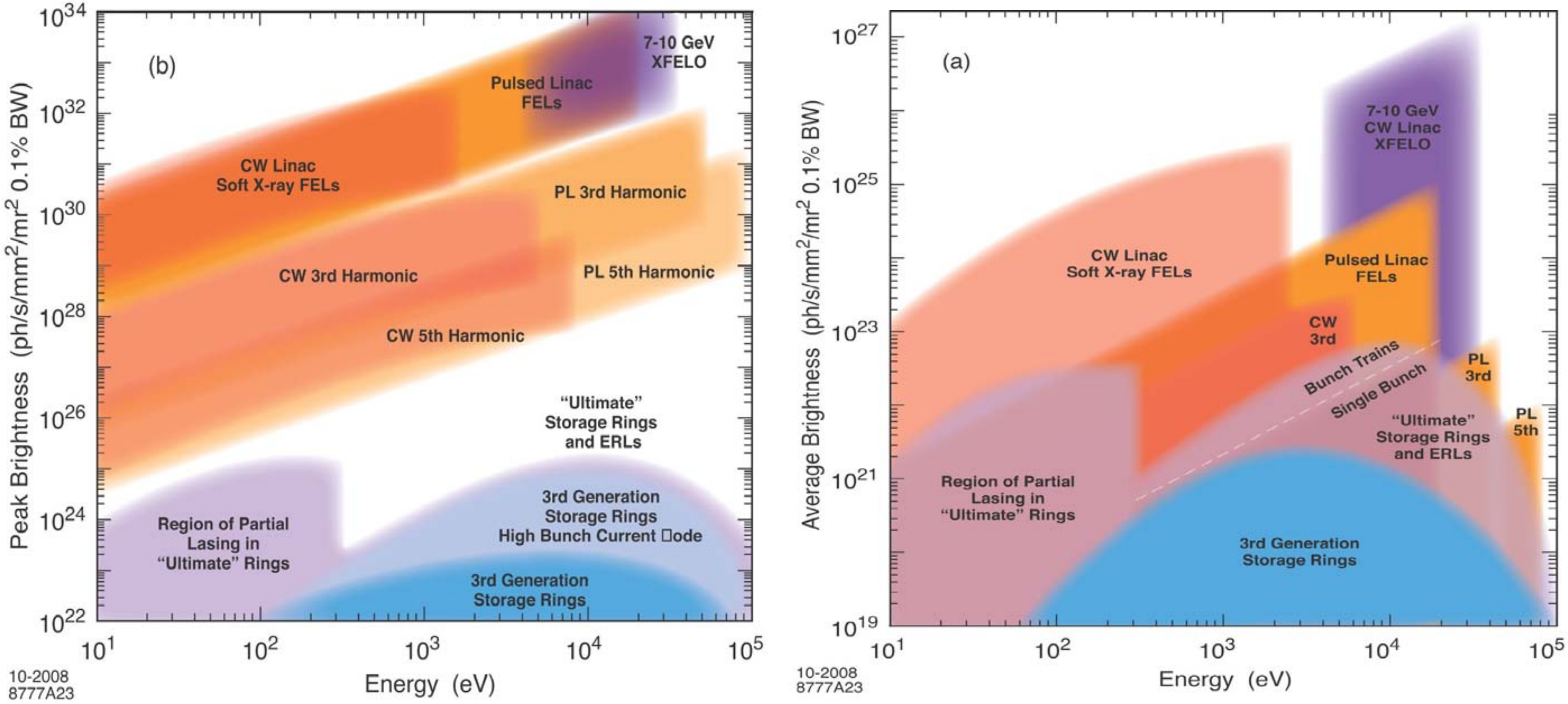
Spectral Brightness



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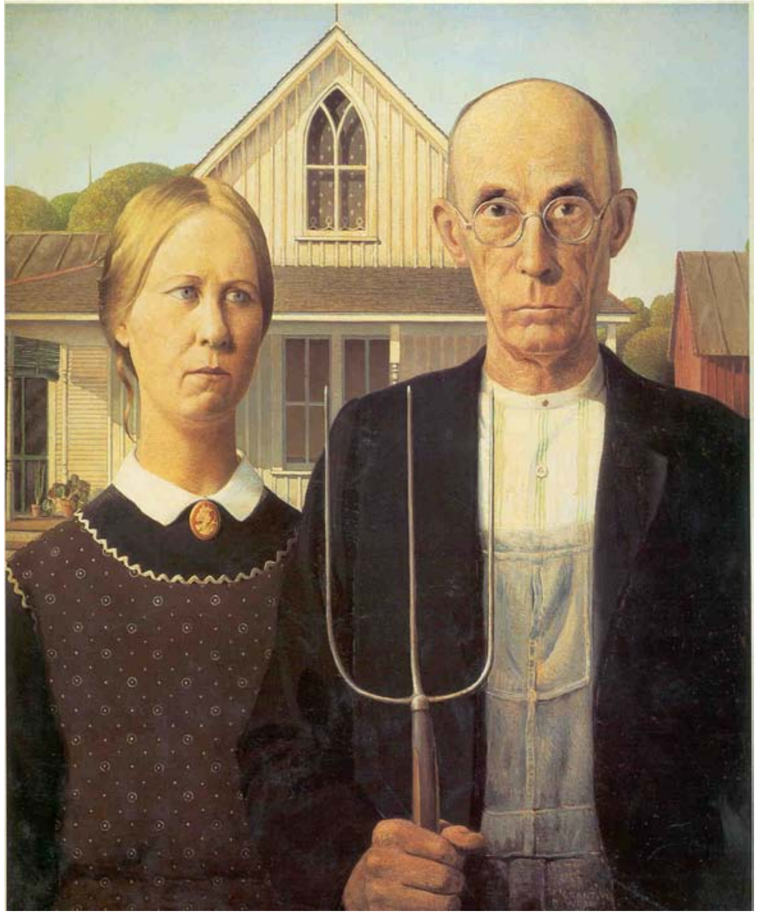
Comparative Light Source Performance

rings



FELs

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- What metrics characterize emerging light sources?
- Are there some new metrics needed (and that might exonerate ring-based sources)?
- This talk will touch lightly on complex topics
- Most points are obvious, no profound conclusions
- Maybe more questions asked than answered

What Do SR Users Care About?

Some user answers:

A lot of photons into a small spot	A lot of photons into a large area
A lot of coherent photons	A high coherent fraction
A lot of photons in a short pulse	A lot of photons in a long pulse
A high pulse repetition rate	A low pulse repetition rate
Not too many photons	nm spatial resolution
Femtosecond pump-probe timing stability	0.1% intensity stability
50 keV photons	280 eV photons
10^{-6} energy bandwidth (meV)	10^{-2} energy bandwidth
fast switched polarization	etc…..

Paraphrased:

Maximum number of “usable” photons for an experiment in a minimum time

experiment = experiment “acceptance phase space”

“acceptance phase space” not easy to define for many experiments

(2-/4-color mixing, nonlinear multi-photon events, non-linear multidimensional spectroscopy, etc.)

Important Metrics for Usable Photons

flux to sample	photons/pulse
coherent flux	coherent photons/pulse
repetition rate	control of timing/synchronization
timing stability	timing synchronization
bunch length	control of bunch length
energy range	energy tunability
multiple energies (2-/4-color)	polarization switching
energy bandwidth	energy resolution
beam size	beam divergence
beam stability	power density

etc.…

Many parameters are captured with the traditional metrics:

peak brightness	average brightness

(electron current/charge, energy, emittance, bunch length,…)

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Usable Photons

- Photons delivered to experiment acceptance phase space V_{exp} (up to 6D):

$$\int_{V_{exp}} B(\lambda)dV$$

- High brightness does not necessarily mean more usable photons if source phase space "underfills" or is not matched to V_{exp}
  - **Protein crystal has large acceptance $\Rightarrow$ flux more important than brightness**
  - **X-ray absorption, x-ray emission and photoemission are insensitive to angular divergence of incident photons $\Rightarrow$ do not require lateral coherence. Small source size (i.e. small β_x) is important**
  - **An experiment having 1% energy acceptance does not benefit any more from a source having 10^{-6} energy BW than from one having 10^{-3} BW**
- Usable peak brightness and flux may be limited by sample damage, x-ray optics, detectors, signal processing rates, etc.

these factors might be included in defining acceptance phase space

Spectral Brightness and Coherent Fraction

Spectral brightness: photon density in 6D phase space

$$B_{avg}(\lambda) \propto \frac{N_{ph}(\lambda)}{(\varepsilon_x \oplus \varepsilon_r(\lambda))(\varepsilon_y \oplus \varepsilon_r(\lambda))(s \cdot \%BW)}$$

$\varepsilon_{x,y}$ = electron emittance

ε_r = photon emittance = $\lambda/4\pi$

$$B_{pk}(\lambda) \propto \frac{N_{ph}(\lambda)}{(\varepsilon_x \oplus \varepsilon_r(\lambda))(\varepsilon_y \oplus \varepsilon_r(\lambda))(\sigma_t \cdot \%BW)}$$

σ_t = bunch length

Coherent fraction:

$$f_{coh}(\lambda) = \frac{\lambda / 4\pi}{(\varepsilon_x \oplus \varepsilon_r(\lambda))} \cdot \frac{\lambda / 4\pi}{(\varepsilon_y \oplus \varepsilon_r(\lambda))}$$

Fourier Transform Limits

Size-divergence transform limit (diffraction limit):

Expresses fundamental coupling between beam size and angular divergence resolution and defines complete transverse coherence.

Diffraction-limited emittance for transverse Gaussian electron beam:

$$\varepsilon_{diff}(\lambda) = \frac{\lambda}{4\pi}$$

(= 8 pm-rad @ 1 Å)

Time-energy transform limit:

Expresses the fundamental coupling between energy resolution and time resolution and defines complete temporal coherence.

For Gaussian pulse intensity:

$$\Delta t \cdot \Delta E_{ph} = \frac{h}{4\pi}$$

(= 3.3x10^{-4} ps(rms) eV(rms))

In terms of fractional bandwidth:

$$\frac{\Delta E_{ph}}{E_{ph}} = \frac{h}{4\pi E_{ph}\Delta t} = \frac{\lambda}{4\pi c}$$

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Redefined Brightness ?

New and future light sources are pushing towards transform-limited performance

Peak brightness in terms of transform-limited phase space volume – "coherence volume" V_{coh}:

$$B_{pk}(\lambda) = \frac{N_{ph}(\lambda)}{V_{coh}(\lambda)}$$

$$V_{coh}(\lambda) \sim \frac{\lambda}{4\pi} \cdot \frac{\lambda}{4\pi} \cdot \frac{\lambda}{c4\pi} = \frac{1}{c}\left(\frac{\lambda}{4\pi}\right)^3$$

$V_{coh}(1Å) = 1.17 \times 10^{-27}\ s \cdot mm^2 \cdot mrad^2 \cdot 0.1\%\ BW$

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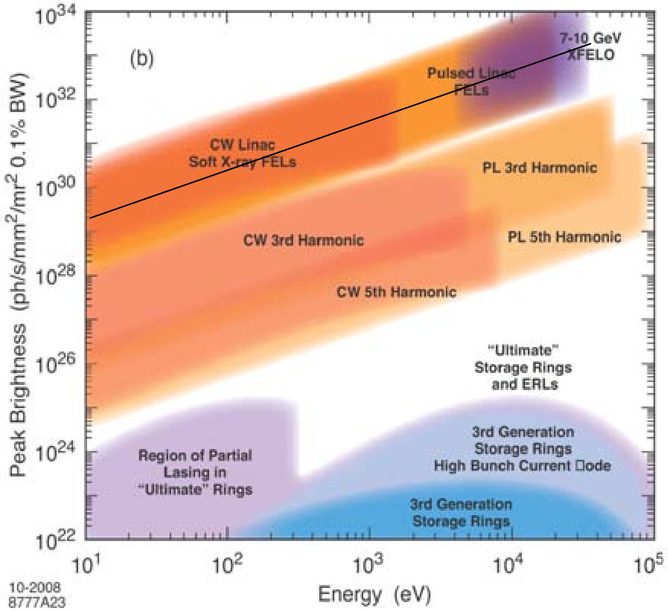
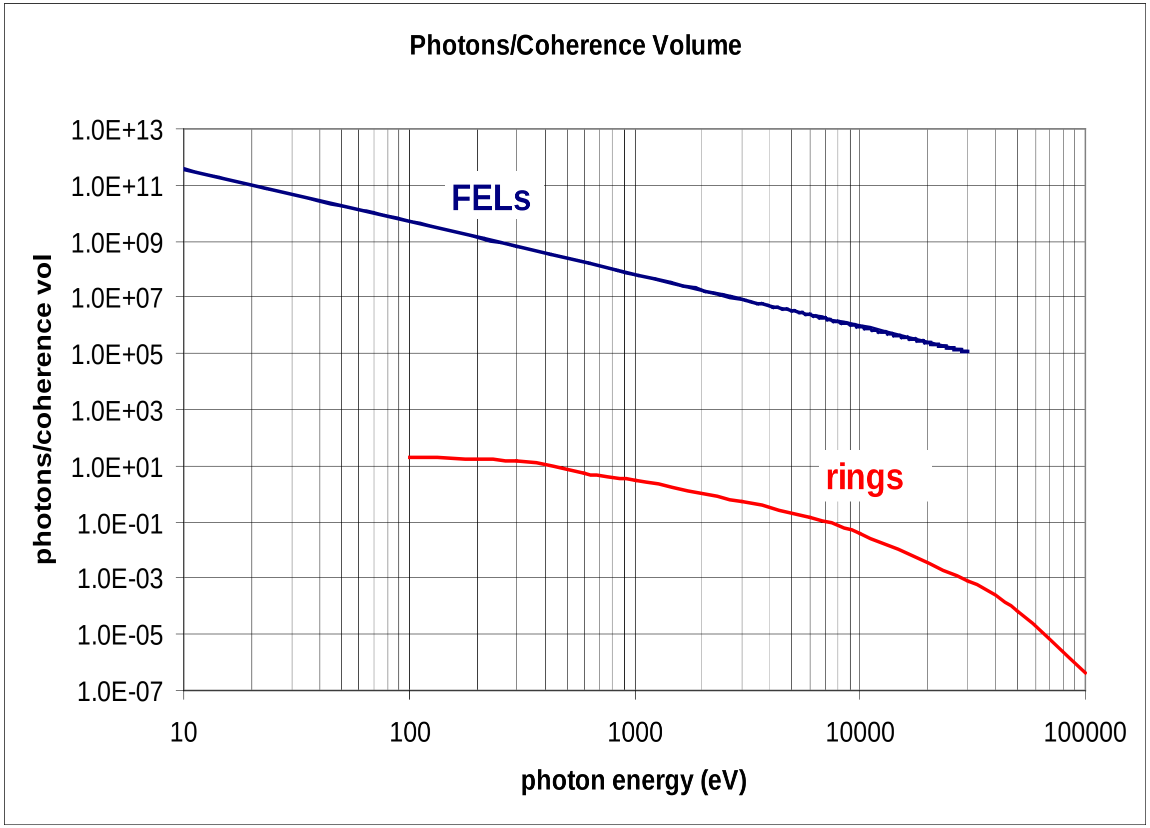
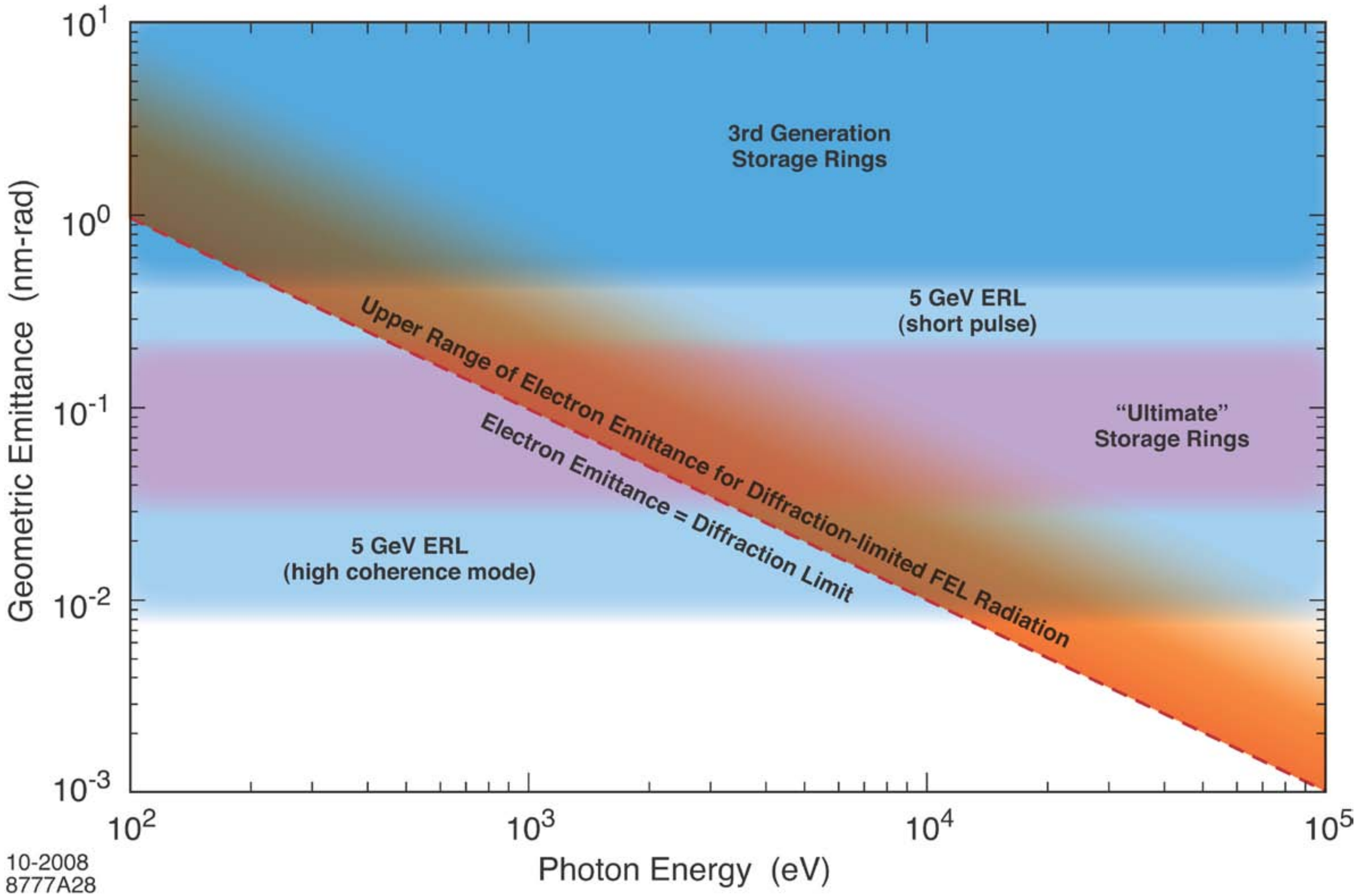
Photons per "Coherence Volume"



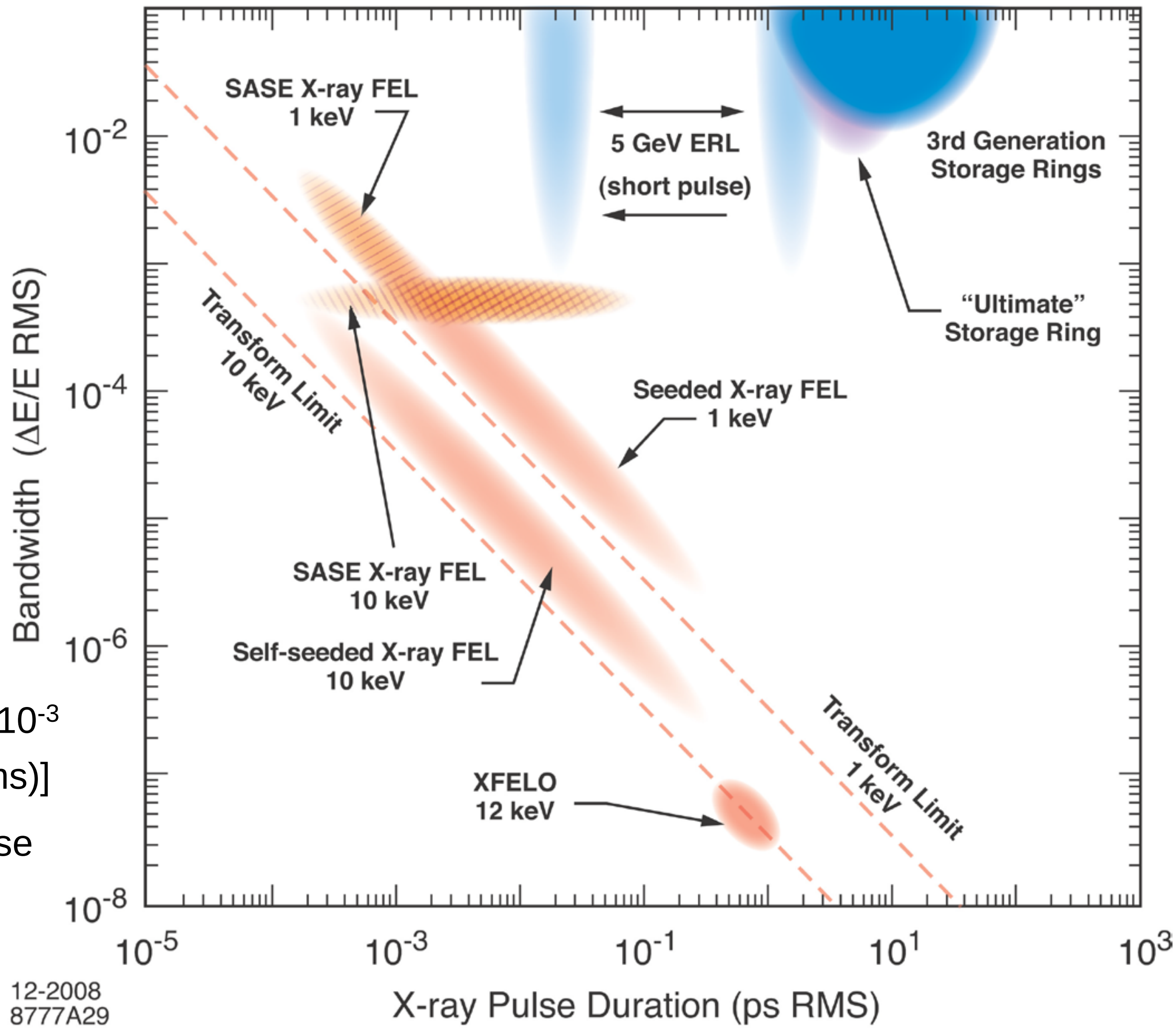


Diffraction-Limited Emittance



Diffraction limit: $\varepsilon_{ph} = \lambda/4\pi$

Energy Bandwidth vs. Pulse Length

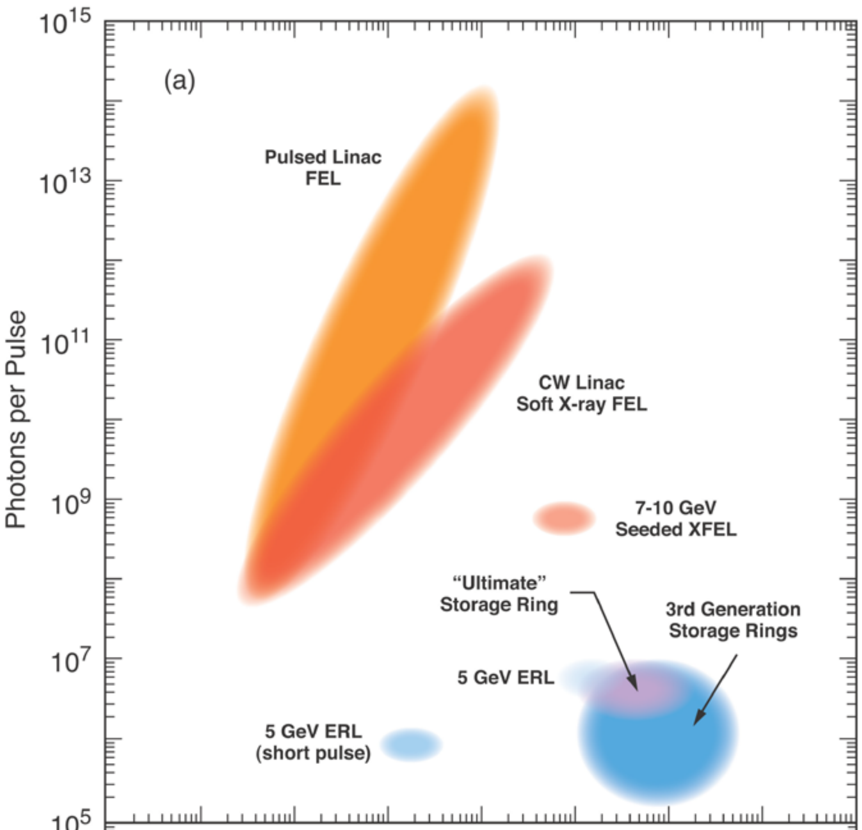


$\Delta t \cdot \Delta E = 0.33 \times 10^{-3}$

[ps(rms)·eV (rms)]

for aussian pulse

X-ray Source Temporal Performance



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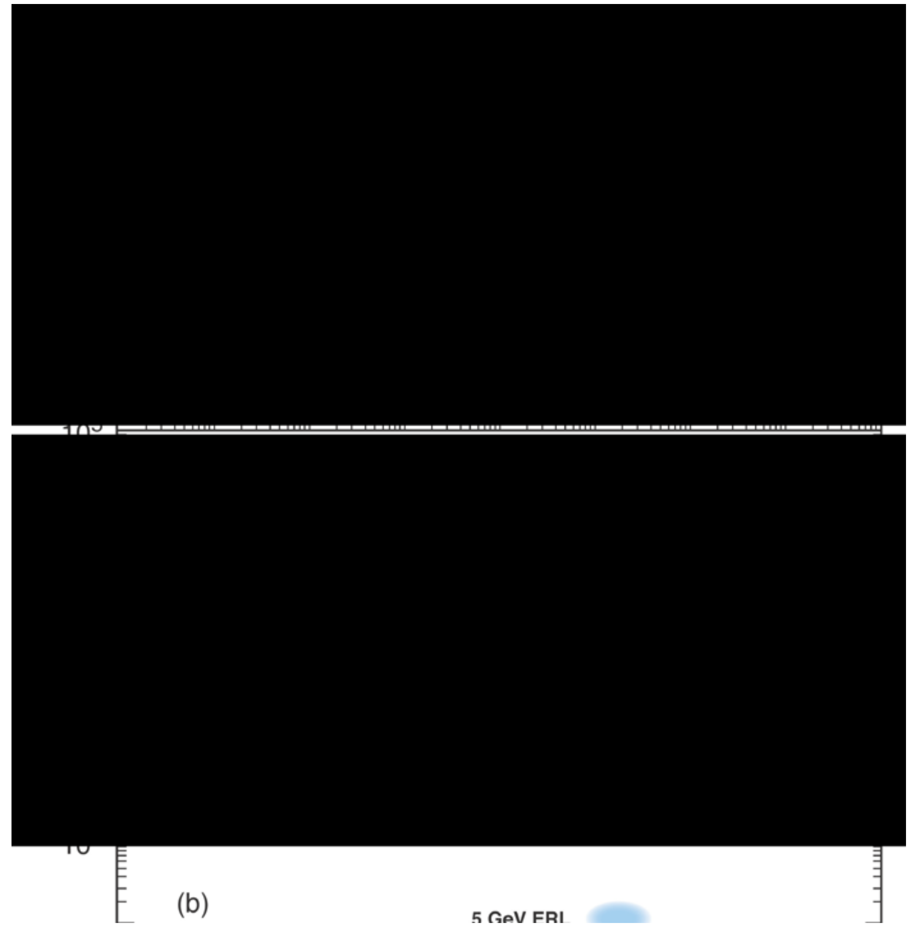

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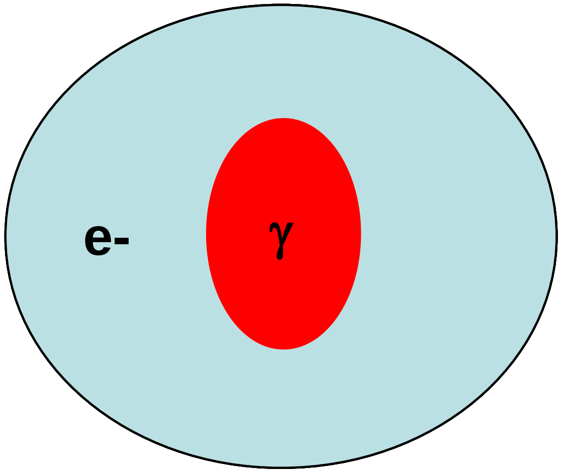
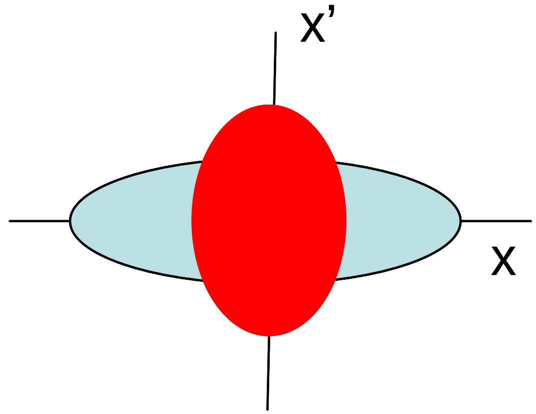
Limitations to Reaching Transform Limit -Transverse

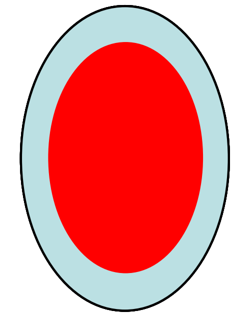
Electron-photon phase space matching:



high electron emittance



low electron emittance, mismatched



low electron emittance, matched

Insertion device parameters

X-ray optics: can they preserve emittance and coherence?

Limitations to Reaching Transform Limit - Longitudinal

Spontaneous undulator radiation

Inherent bandwidth: $$\frac{\Delta\lambda}{\lambda} = \frac{1}{nN_{und}}$$

N_{und} = # undulator periods, n = harmonic #

Must be convolved with electron energy spread:

storage ring: $\sigma_E = \sim 10^{-3}$ **linac/ERL: $\sigma_E = \sim 10^{-4}$**

But: BW at experiment determined by monochromator (with loss of intensity)

FELs

SASE: BW determined by cooperation length. For ultra-short bunches, cooperation length can approach the bunch length; (large) bandwidth can be close to the transform limit.

Seeded FEL and XFELO: BW approaches or reaches transform limit

X-ray optics: can they preserve temporal coherence?

Monochromators may not be needed!

Limits to Beam Parameters – cont.

Other limits:

- photons/pulse and flux

  >~10^9 ph/pulse can cause sample damage

  FEL users finding ways to avoid damage from much higher ph/pulse (10^{12}?) – ultrashort pulses, energy detuning,etc

- repetition rate: too low or too high (detector processing rates, etc)
- **stability!!**
- cost
- …..

Factors that prevent reaching performance potential may be considered to be metrics

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Other Metrics

Some important light source performance factors not captured by preceding metrics:

- polarization control
- timing/synchronization
- various operating modes
- # simultaneous experiments
- construction cost
- operation cost
- etc.

New metric:

$$\frac{\#\,\text{usable photons}/\text{pulse} \cdot \text{usable rep rate} \cdot \#\ \text{stations} \cdot \#\,\text{modes} \cdot \ldots.}{\text{facility cost}}$$

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The Need for Complementary Light Sources

XFELs:

- unprecedented x-ray peak brightness, coherence and short pulse length
- control of longitudinal phase space
- femtosecond-level pump-probe capabilities
- A revolutionary tool for photon science

Ring-based sources:

- highly stable high average brightness (and coherence), low peak brightness, high repetition rates
- wide energy spectrum and ultrahigh energy resolution
- picosecond pulses match timescale of electron-phonon coupling and allow electronic system to remain “cool” during and after the x-ray probe
- future ring-based sources will push toward the exploration of the combined minimum phase space boundary of order 1 nm, 1 meV and 10 ps
- support a large number of photon beam lines and serve a large number of diverse users simultaneously

ISEMS

Integrated Source and Experiment Metrics System