Light Source Design – Part 2: Storage Ring Technology

Tuesday 23 Nov 2010 at 09:00 (01h00')

Primary authors : Dr. HETTEL, Robert (SLAC)

Co-authors :

Presenter : Dr. HETTEL, Robert (SLAC)

Light Source Design:
Source Types, Parameters and Metrics

Robert Hettel, SLAC

Mexican Light Source Workshop

November 22-24, 2010

Outline

- Light source types and choices
- Light source parameters
- User needs
- Defining “usable” photons
- Limits to reaching “ultimate” performance
- A new performance metric…
- The need for complementary sources

Choosing a Light Source Type

Choosing a Light Source Type

Why build a light source?

- To serve an X-ray user facility? If so, what is size of user community?
- To serve as a tool to train and develop accelerator physicists, engineers and other technologists?
- To do both?

Choosing a Light Source Type

Why build a light source?

- To serve an X-ray user facility? If so, what is size of user community?
- To serve as a tool to train and develop accelerator physicists, engineers and other technologists?
- To do both?

What are funding resources?

- For initial construction?
- For ongoing operation?
- …

Choosing a Light Source Type

Why build a light source?

- To serve an X-ray user facility? If so, what is size of user community?
- To serve as a tool to train and develop accelerator physicists, engineers and other technologists?
- To do both?

What are funding resources?

- For initial construction?
- For ongoing operation?
- …

What performance is desired?

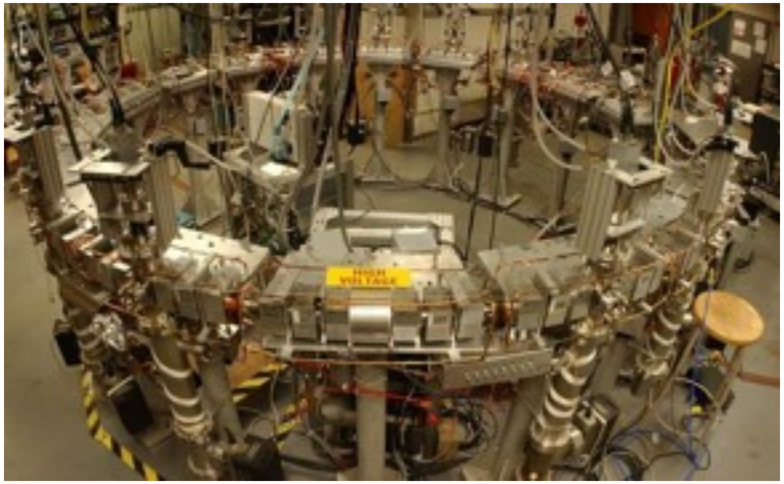
- Parameters of interest?
- Operating hours per year?
- Reliability?
- …

Types of Light Sources

- Storage rings
- ERLs
- FELs
- Compact sources
- …..

Storage Rings

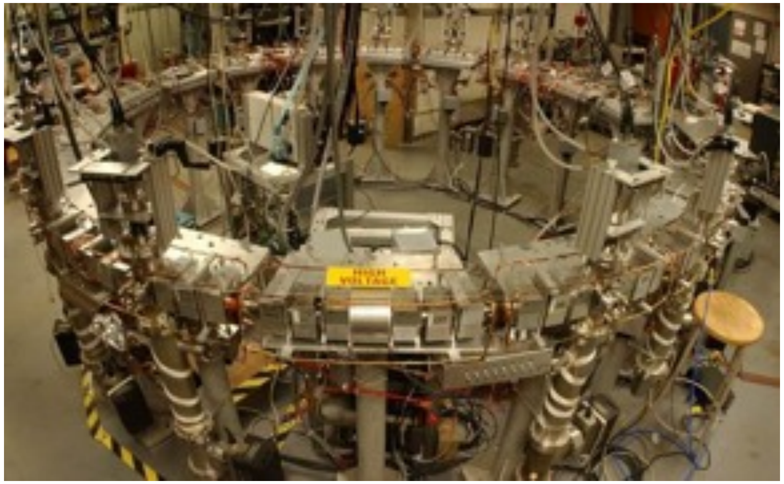
Storage Rings



UMER
E_{e-} = 10 keV, C = 12.5 m

research accelerator with space charge-dominated beam

Storage Rings

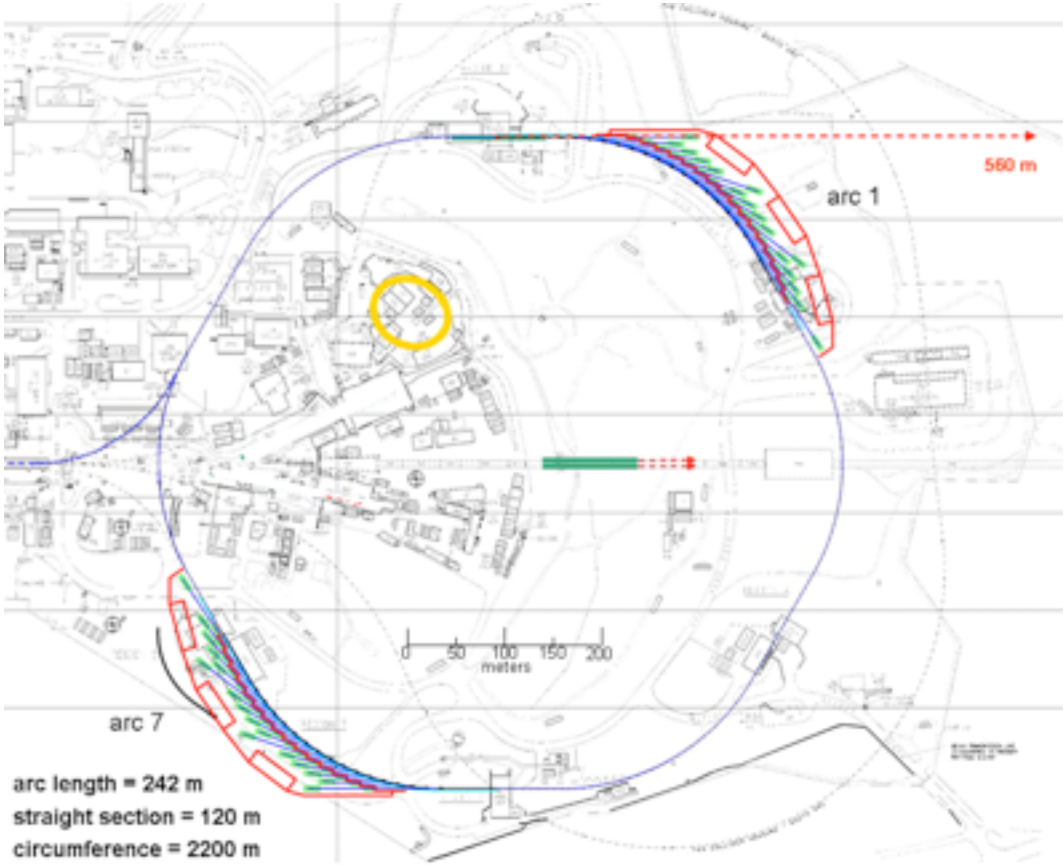


UMER
E_{e-} = 10 keV, C = 12.5 m

research accelerator with space charge-dominated beam

PEP-X
E_{e-} = 4.5 GeV, C = 2200 m

diffraction-limited ultimate ring



Storage Rings – cont.

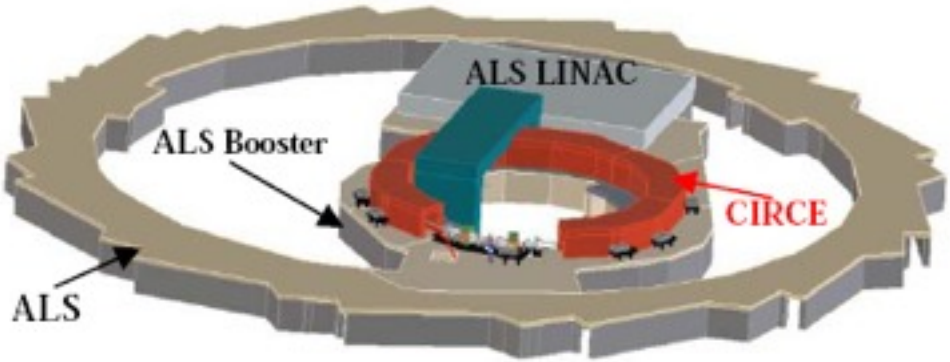
NSLS VUV Ring
E_{e-} = 808 MeV, 1 A, C = 51 m

Bursting CSR THz/IR emission

Storage Rings – cont.

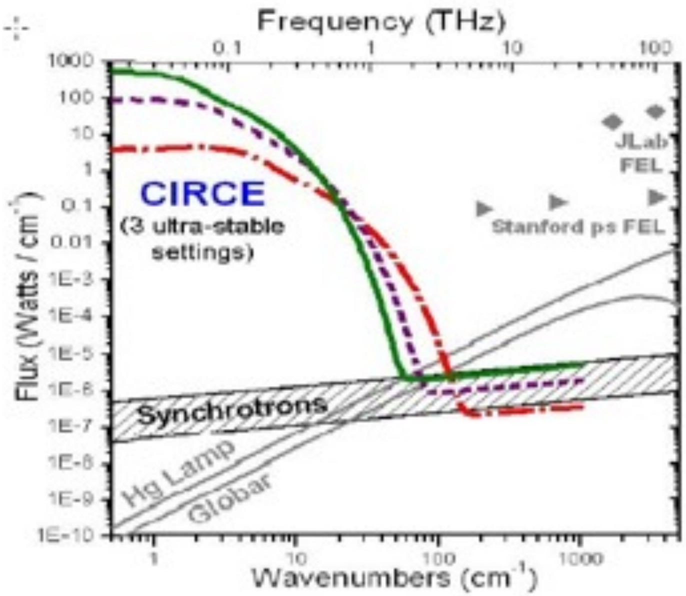
NSLS VUV Ring
E_{e-} = 808 MeV, 1 A, C = 51 m

Bursting CSR THz/IR emission

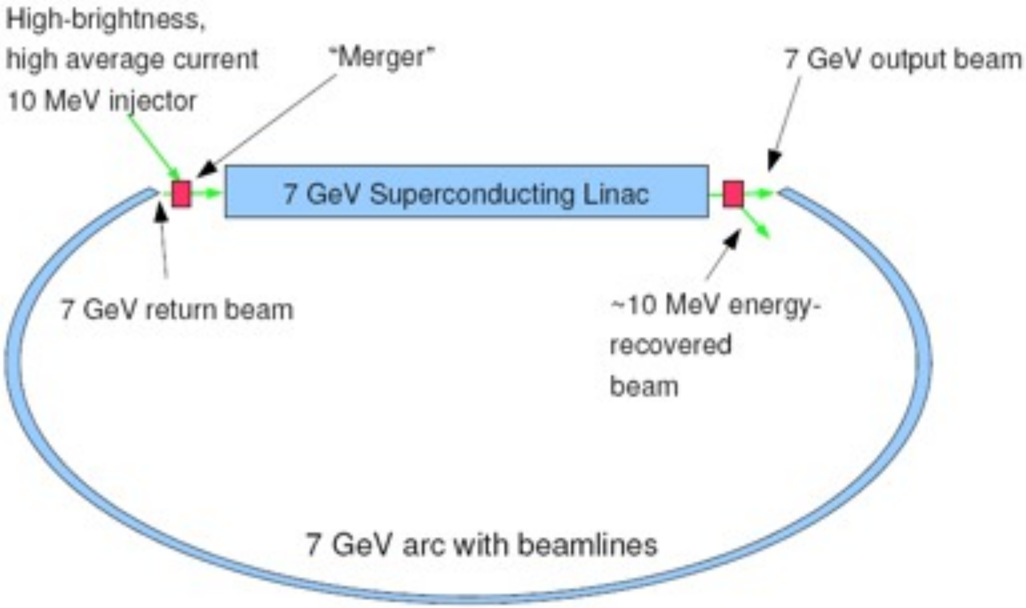


CIRCE at ALS
E_{e^-} = 600 MeV, 1 A, C = 66 m

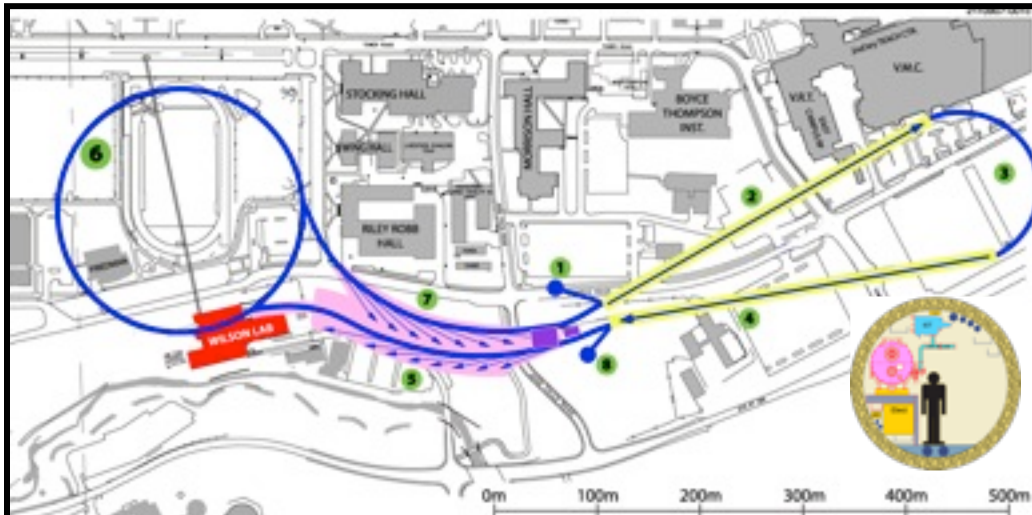
Coherent THz/IR emission

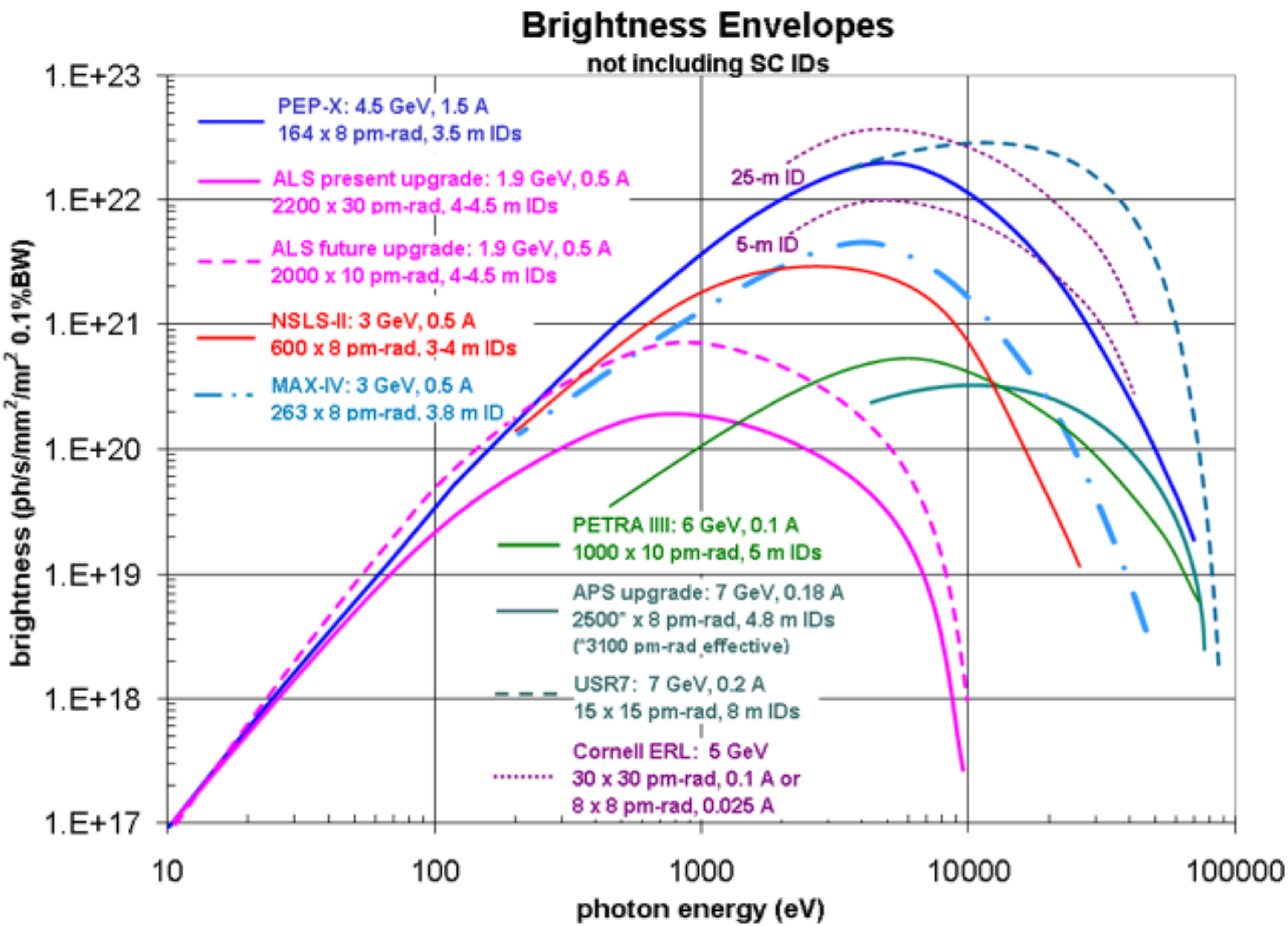


Energy Recovery Linacs



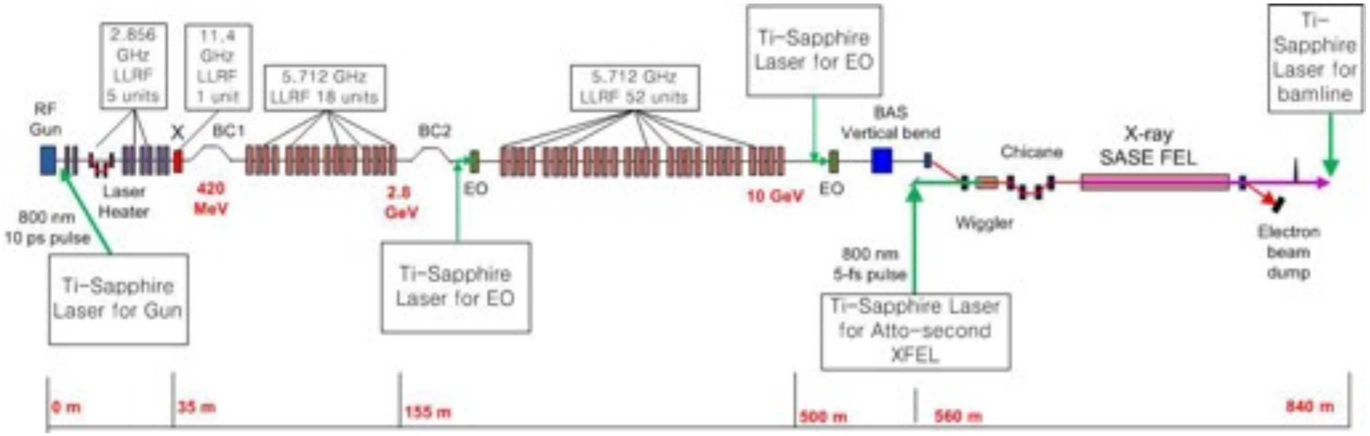
5 GeV Cornell ERL




Brightness Envelopes
not including SC IDs
PEP-X: 4.5 GeV, 1.5 A
164 x 8 pm-rad, 3.5 m IDs
ALS present upgrade: 1.9 GeV, 0.5 A
2200 x 30 pm-rad, 4-4.5 m IDs
ALS future upgrade: 1.9 GeV, 0.5 A
2000 x 10 pm-rad, 4-4.5 m IDs
NSLS-II: 3 GeV, 0.5 A
600 x 8 pm-rad, 3-4 m IDs
MAX-IV: 3 GeV, 0.5 A
263 x 8 pm-rad, 3.8 m ID
25-m ID
5-m ID
PETRA IIII: 6 GeV, 0.1 A
1000 x 10 pm-rad, 5 m IDs
APS upgrade: 7 GeV, 0.18 A
2500* x 8 pm-rad, 4.8 m IDs
(*3100 pm-rad effective)
USR7: 7 GeV, 0.2 A
15 x 15 pm-rad, 8 m IDs
Cornell ERL: 5 GeV
30 x 30 pm-rad, 0.1 A or
8 x 8 pm-rad, 0.025 A
brightness (ph/s/mm²/mr² 0.1%BW)
1.E+23
1.E+22
1.E+21
1.E+20
1.E+19
1.E+18
1.E+17
10
100
1000
10000
100000
photon energy (eV)

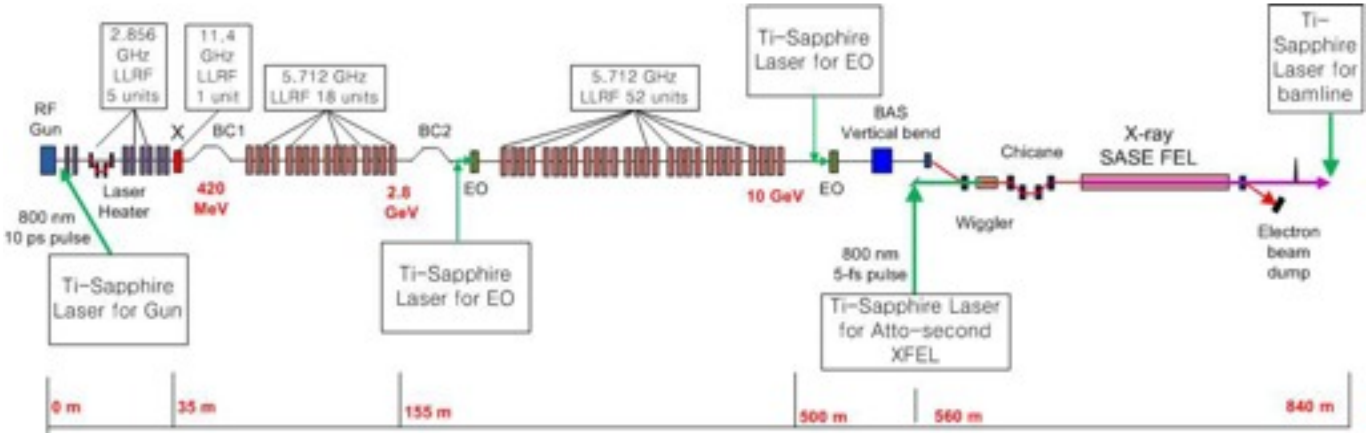
Free Electron Lasers

Free Electron Lasers

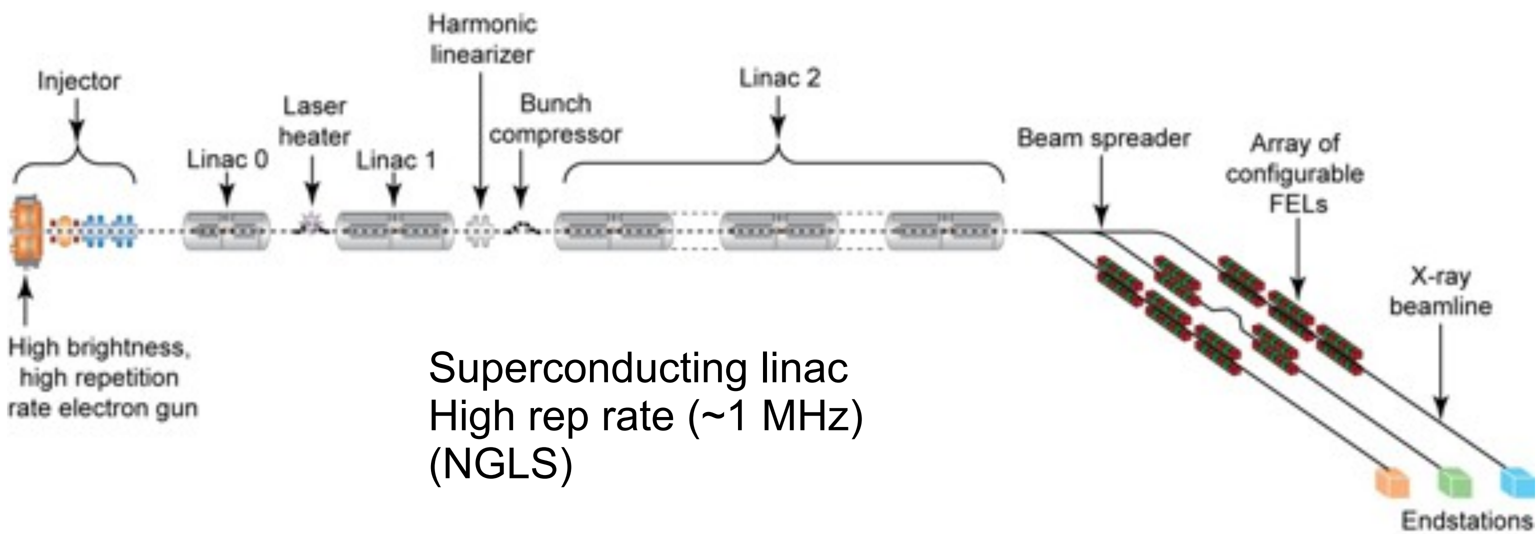


Normal conducting linac
Low rep rate (<~1 KHz)
(PAL XFEL)

Free Electron Lasers



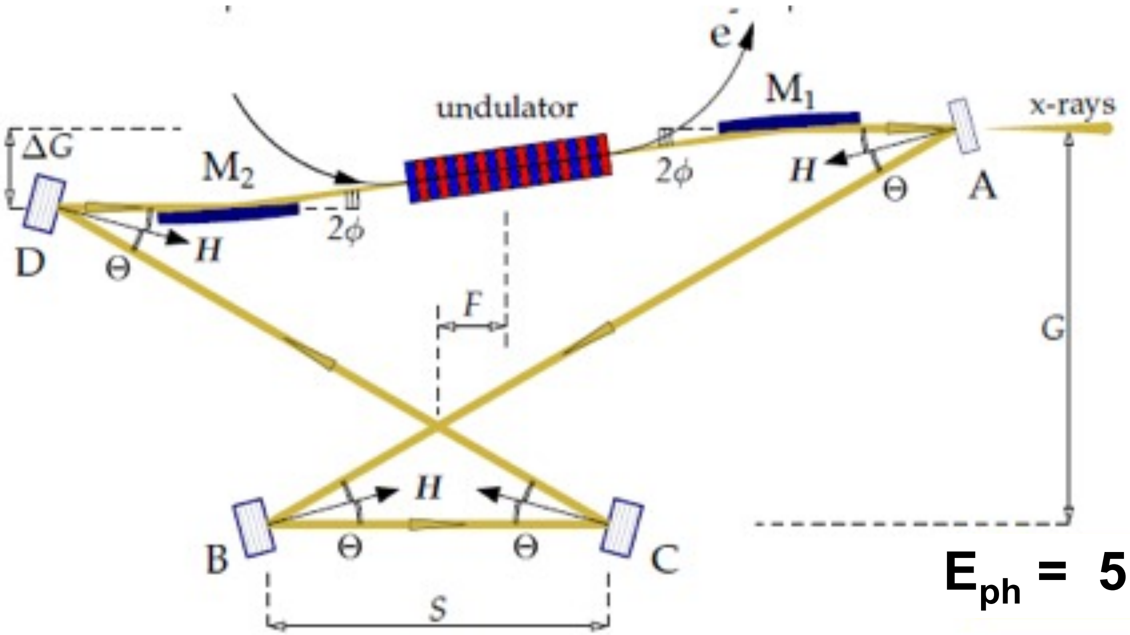
Normal conducting linac
Low rep rate (<~1 KHz)
(PAL XFEL)



Superconducting linac
High rep rate (~1 MHz)
(NGLS)

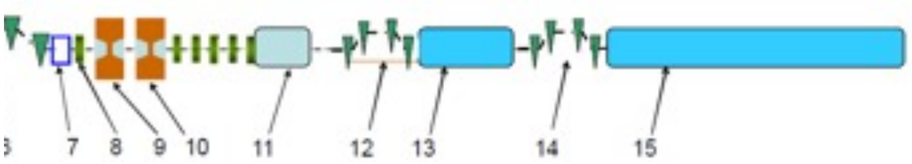
SLAC NATIONAL ACCELERATOR LABORATORY

X-ray FEL Oscillator (XFELO)



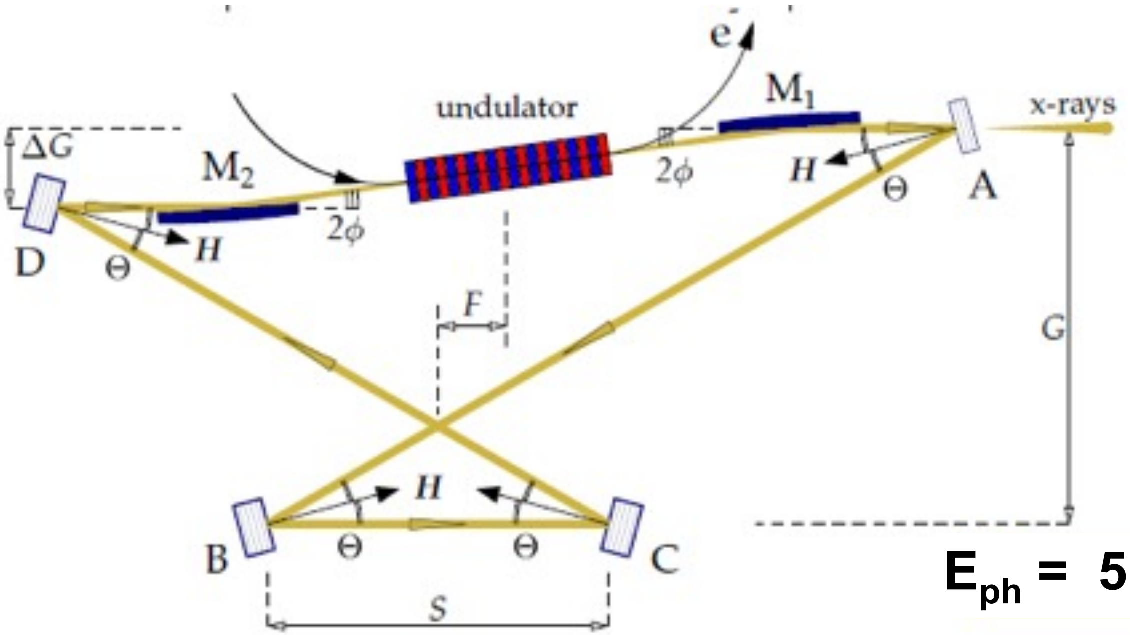
K-J Kim

E_{ph} = 5-25 keV



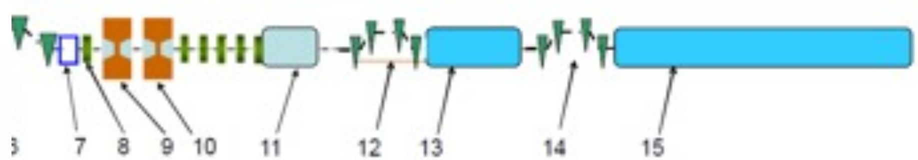
>~1 MHz, 7-GeV linac

X-ray FEL Oscillator (XFELO)



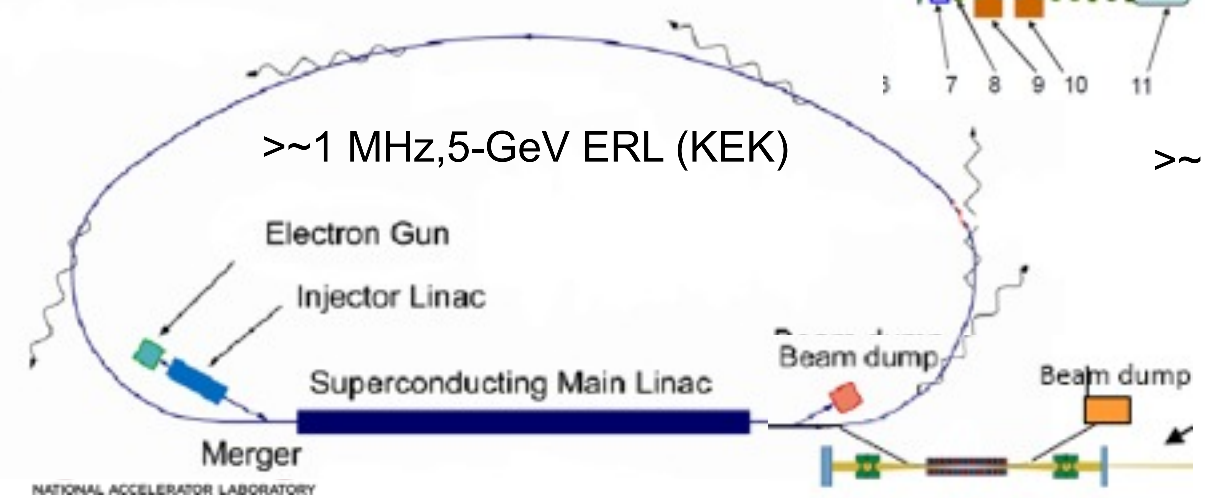
K-J Kim

E_{ph} = 5-25 keV



>~1 MHz, 7-GeV linac

>~1 MHz,5-GeV ERL (KEK)



Compact X-ray Sources

- Fixed Tubes and Rotating Anodes
  - Electron beam colliding with metal target—well known
  - Rigaku FR-E Model for PX has flux = $4x10^9$ ph/s in 300 μm
- Plasma Sources
  - Laser beam colliding with fixed metal target
  - Very low time average flux, but short (fs) pulses
- Inverse Compton Sources
  - Laser beam colliding with electron bunch
  - Various demonstrations with warm linacs and large conventional storage rings
  - Lyncean Technologies developing "table-top"synchrotron-driven source

D. Moncton, MIT

- HHG laser/gas sources (for EUV, soft x-ray)

Inverse Compton X-ray Sources

Laboratory	Geometry	Energy	Rep. Rate	Photons/pulse
LBL	90°	30 keV	2 Hz	10^4-10^5
BNL	180°	6 keV	0.03 Hz	10^7-10^8
LLNL (PLEIADES)	180°	40-140 keV	10 Hz	10^7
NRL	180°	0.4 keV	~0.01 Hz	10^7/macro-pulse
FESTA	90°/180°	2.3/4.6 keV	10 Hz	$10^4/10^5$
Vanderbilt Univ.	180°	10-50 keV	~0.01 Hz	10^9-10^{10} **
Univ. Tokyo, UTNL*	180°	40 keV	10 Hz	10^8/macro-pulse**
LLNL(T-REX)*	180°	0.1-1 MeV	10 Hz	10^8-10^9 **
Kharkov Institute*	170°/30°	6-900 keV	40-700 MHz	10^5**

*** Under Development**

**** Design value**

D. Moncton, MIT

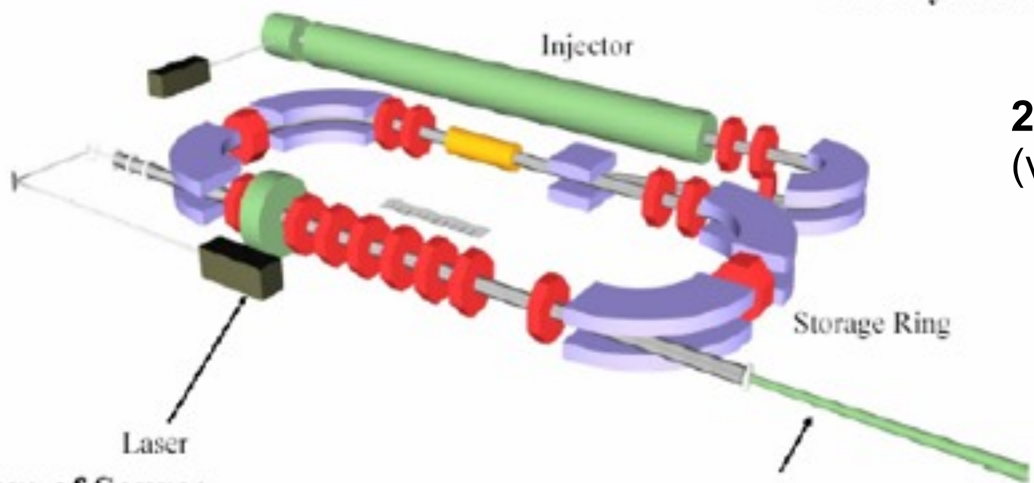
Inverse Compton X-ray Sources – cont.

Lyncean Technologies Compact Source Concept

A Conceptual Picture of the CLS

(The 30 cm ruler in the middle is shown for scale.)

Courtesy of Ron Ruth



25-MeV injector
(variable energy)

Parameters of Source

Average flux	10^{12} photons/sec
Source size	100 microns

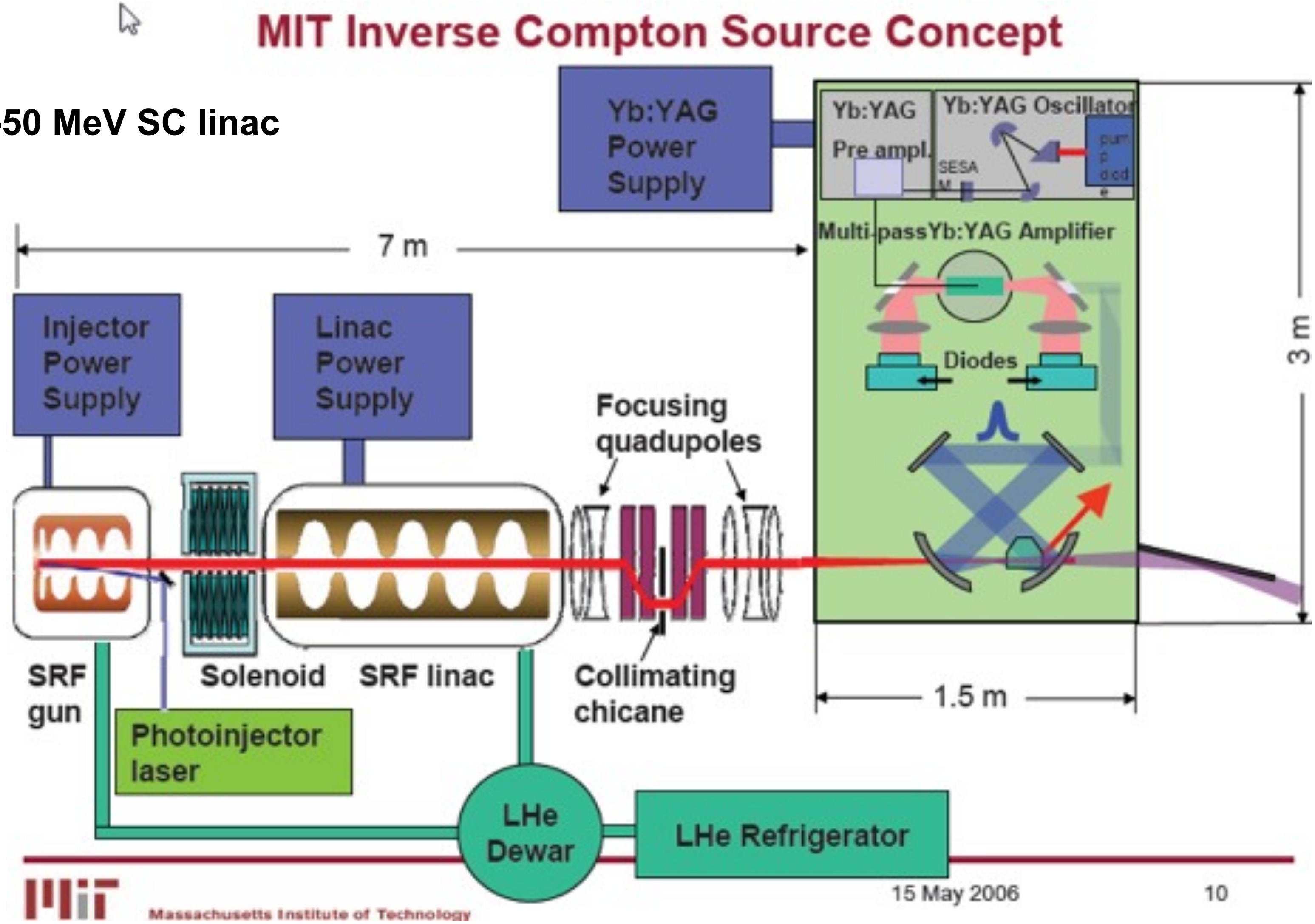
Source Spot Size†	30 μm radius	matched beam waists
Source Divergence†	≈ 3 mrad	
Source Brightness	$\gtrsim 10^{11}$	ph/s/mm^2/mrad^2/0.1% BW
X-ray Energy Range‡	12 keV $\pm$ 6 keV	1 Å = 12.4 keV

*Typical value for a beamline monochromator bandwidth.
†Spot size and divergence correspond to $\varepsilon^n \simeq 1 \times 10^{-7}$.
‡Peak energy of X-rays scales as square of (tunable) electron beam energy.

SLAC NATIONAL ACCELERATOR LABORATORY

Inverse Compton X-ray Sources – cont.

15-50 MeV SC linac



D. Moncton, MIT

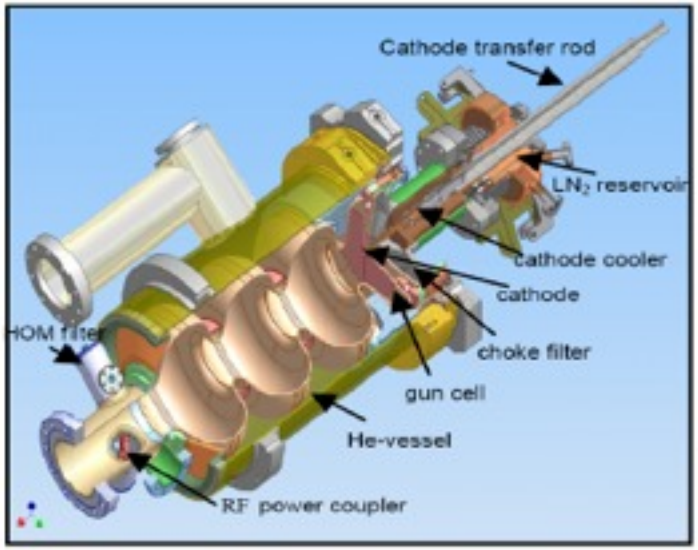
~6 x 10^{14} brightness

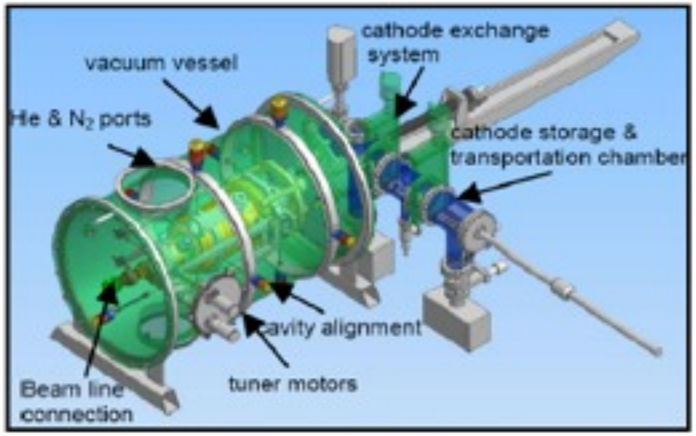
~10^{12} ph/s flux in 1% BW

MIT Inverse Compton Source – cont.

Superconducting RF Electron Gun

Rossendorf design to be manufactured by Accel Instruments





Cryostat with cathode exchange system.

1.3 GHz RF frequency, Cs_2 Te cathode
Current = 1 mA
Charge = 100 pC per pulse at 10 MHz
Exit energy = 8 MeV

D. Moncton, MIT

Light Source Parameters

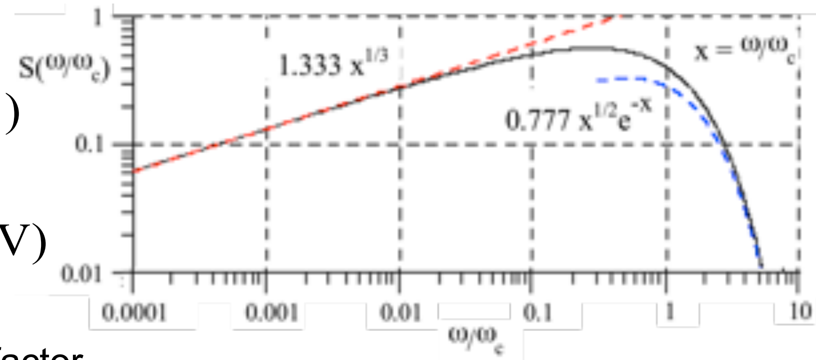
- Spectrum
- Spectral flux density
- Beam power
- Beam dimensions
- Brightness
- Other…

Photon Spectrum and Spectral Flux Density

K-J Kim

Dipole spectral flux density (per horizontal mrad, integrated over vertical angle):

$$\frac{dF_{dip}(\omega)}{d\theta} = 2.457 \times 10^{16} \frac{\Delta\omega}{\omega} E_{e-}^{\ 2}(\mathrm{GeV})\, I(A)\, S(\omega/\omega_c)$$



$$\omega_c = \frac{E_c}{h}; \quad E_c(\mathrm{keV}) = \frac{3hc\gamma^3}{2\rho} = 0.665 B(T) E_{e-}^{\ 2}(\mathrm{GeV})$$

ρ = dipole bend radius, B(T) = dipole field, γ = relativistic factor

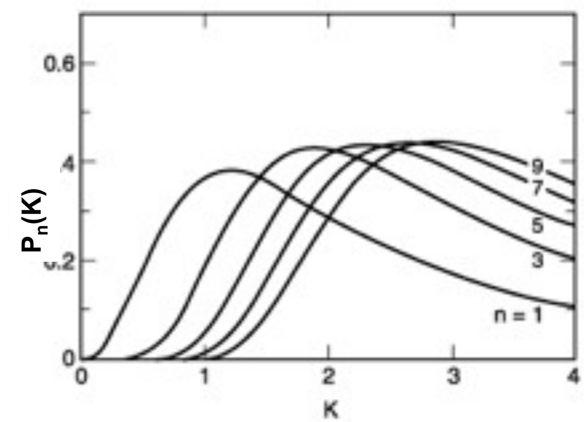
Wiggler spectral flux density:

$$\frac{dF_{wigg}(\omega)}{d\theta} =\sim N_{wigg} \frac{dF_{dip}(\omega)}{d\theta} \qquad N_{wigg} = \#\,\mathrm{wiggler\ poles}$$

Undulator spectral flux density:

$$\left.\frac{d^2F_{und}(\omega_n)}{d\theta\, d\varphi}\right|_{\varphi,\theta=0} = 1.744 \times 10^{14} \frac{\Delta\omega}{\omega} N_u^{\ 2} E_{e-}^{\ 2}(\mathrm{GeV})\, I(A)\, P_n(K)$$

N_u = # undulator periods



Photon Beam Power

Dipole radiation:

$$\frac{dP_{dip}}{d\theta}\,(W/mrad) = 14.09\,\frac{E_{e-}{}^{4}(GeV)}{\rho\,(m)}\,I(A)$$

$$P_{Tot-dip}\,(kW) = 88.5\,\frac{E_{e-}{}^{4}(GeV)}{\rho\,(m)}\,I(A)$$

Insertion device radiation:

$$P_{ID}(kW) = 0.633\;E^{2}(GeV)\,B_0^2(T)\,L_{ID}(m)\,I(A)$$

Power density (W/mm^2) ~ $E_{e-}{}^{4}$

SLAC NATIONAL ACCELERATOR LABORATORY

Photon Beam Dimensions

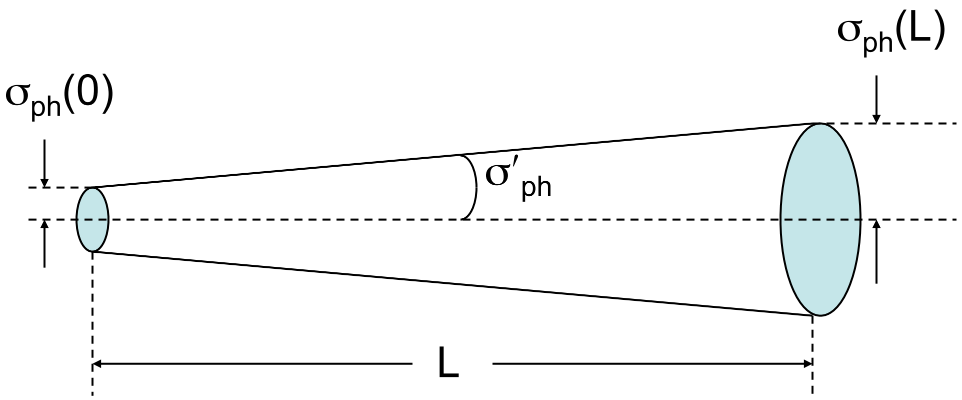
Photon beam size:

- unfocused, vertical plane:

(assume depth of field = 0)

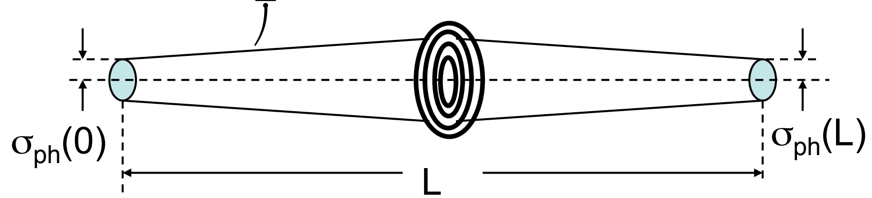
$\sigma_{ph}(L) = [\sigma_{ph}(0)^2 + L^2\sigma_{ph}'^2]^{1/2}$

$\sigma_{ph}(0) = [\sigma_{e-}^2 + \sigma_{diff}^2(\lambda)]^{1/2}$



$\sigma_{e-} = [\varepsilon\beta(s) + (\eta(s)\delta)^2]^{1/2}$

$$\sigma_{diff} = \frac{\lambda}{4\pi\sigma'_{\psi}(\lambda)} \left(= \frac{\sqrt{2L_u\lambda}}{4\pi} \text{ for undulator length } L_u \right)$$

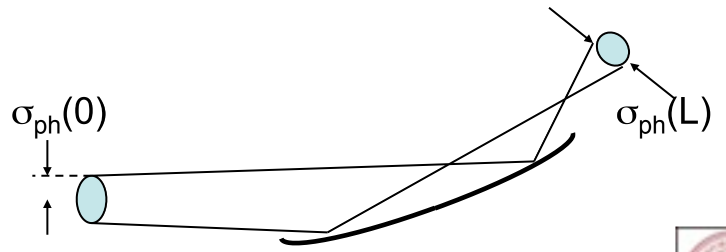


- focused (1:m, m = magnification):

$\sigma_{ph}(L) = m\sigma_{ph}(0)$

(~insensitive to angle)

$\sigma'_{ph}(L) = -\sigma'_{ph}(0)/m$



SLAC NATIONAL ACCELERATOR LABORATORY

Photon Beam Dimensions – cont.

Photon beam divergence:

$\sigma'_{ph}(L) = \sigma'_{ph}(0) = [\sigma'^{\,2}_{e-} + \sigma'^{\,2}_{\psi}]^{1/2}$ $\sigma'_{e-} = [\varepsilon\gamma(s) + (\eta'\delta)^2]^{1/2}$

for dipoles and wigglers:

$$\lambda_c = \frac{2\pi c}{\omega_c} = \frac{hc}{E_c} \qquad h = \text{Planck's const.} = 4.14 \times 10^{-18}\ \text{keV-s}$$

$$E_c(\text{keV}) = \frac{3hc\gamma^3}{2\rho} = 0.665\,B(T)\,E^2(\text{GeV})$$

$$\sigma'_\psi(\lambda) \cong \left[\begin{array}{ll} \dfrac{1.07}{\gamma}\left(\dfrac{\lambda}{\lambda_c}\right)^{1/3} & \lambda >> \lambda_c \\ \dfrac{0.64}{\gamma} & \lambda = \lambda_c. \\ \dfrac{0.58}{\gamma}\left(\dfrac{\lambda}{\lambda_c}\right)^{1/2} & \lambda << \lambda_c \end{array}\right.$$

for planar undulators:
(on-axis, central cone)

$$\sigma'_\psi(n) = \sqrt{\frac{\lambda_n}{2L_u}} = \frac{1}{\gamma}\left[\frac{\lambda_u(1+K^2/2)}{4nL_u}\right]^{1/2} = \frac{1}{\gamma}\left[\frac{1+K^2/2}{4nN_u}\right]^{1/2}$$

n = harmonic # L_u = undulator length λ_u = undulator period N_u = # periods K = ~1

Electron Beam Dimensions

For each conjugate pair, beam occupies phase space ellipse of constant area - or emittance (A = $\pi\varepsilon$)

transverse:

$$\varepsilon = \gamma(s)x^2 + 2\alpha(s)xx' + \beta(s)x'^2 = \text{constant}$$

$$\varepsilon_y \cong k\varepsilon \quad (k = \text{coupling, } k <\sim 0.1)$$

$$\left(\alpha = -\beta'/2 \qquad \gamma = \frac{1+\alpha^2}{\beta}\right)$$

e- beam size:

$$\sigma_x(s) = \sqrt{\varepsilon_x\beta_x(s) + \left(\eta(s)\sigma_{E_{e-}}/E_{e-}\right)^2} \qquad \sigma_y(s) = \sqrt{\varepsilon_y\beta_y(s)}$$

e- divergence:

$$\sigma_{x'}(s) = \sqrt{\varepsilon_x\gamma_x(s) + \left(\eta'(s)\sigma_{E_{e-}}/E_{e-}\right)^2} \qquad \sigma_{y'}(s) = \sqrt{\varepsilon_y\gamma_y(s)}$$

$$\sigma_x\sigma_{x'} = \varepsilon_x \quad \text{when } \alpha = \eta = \eta' = 0$$

longitudinal:

$$\sigma_z = \frac{\alpha c}{\Omega_s}\frac{\sigma_{E_{e-}}}{E_{e-}} = \left(\frac{2\pi h\alpha c^2}{\omega_{RF}^2\cos\phi_s}\frac{E_{e-}}{eV_{RF}}\right)^{1/2}\frac{\sigma_{E_{e-}}}{E_{e-}}$$

$$\sigma_\phi\ (\text{rad}) = \frac{h\alpha_c}{\nu_s}\frac{\sigma_{E_{e-}}}{E_{e-}} \quad \left(= \sim 40\frac{\sigma_{E_{e-}}}{E_{e-}} \text{ for SPEAR3}\right)$$

$$\varepsilon_s = \int_S \frac{\Delta E}{\omega_{rf}}d\phi = \sigma_s\sigma_{\Delta E/E}$$

$\eta(s)$ = lattice dispersion function
α_c= momentum compaction factor

Transverse Beam Dimensions for 3rd Generation Sources

Typical photon beam dimensions

3 GeV 3rd generation source with ε = ~3 nm-rad, 0.1% coupling, E_c = 7.5 keV:

	dipole/wiggler		undulator (**N=100, n=1, E = 2 keV**)	
	hor	vert	hor	vert
σ_{e-} (μm)	75-300	7-20	75-300	7-20
σ'_e (μrad)	10-50	1-3	10-50	1-3
σ_{diff} (E_c) (μm)	0.12	0.12	3.6	3.6
σ'_ψ (E_c) (μrad)	107	107	14	14
σ_{ph} (E_c) (μm)	**75-300**	**7-20**	**75-300**	**8-21**
σ'_{ph} (E_c) (μrad)	**mrads**	**107**	**17-52**	**14**

For 100-period undulator, n = 7 (~12 keV), **σ'_{ph} (n = 7) = 5-6 μrad**

NATIONAL ACCELERATOR LABORATORY

Spectral Brightness and Coherent Fraction

Spectral brightness: photon density in 6D phase space

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

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

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

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

σ_t = bunch length

Spectral Brightness and Coherent Fraction

Spectral brightness: photon density in 6D phase space

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

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

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

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

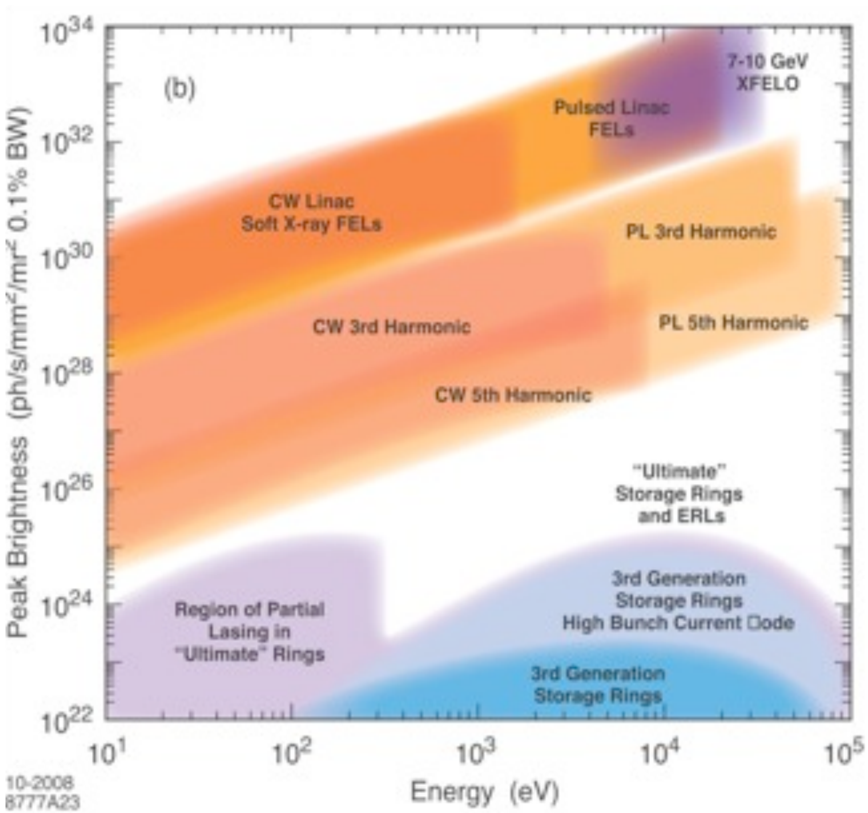
σ_t = bunch length

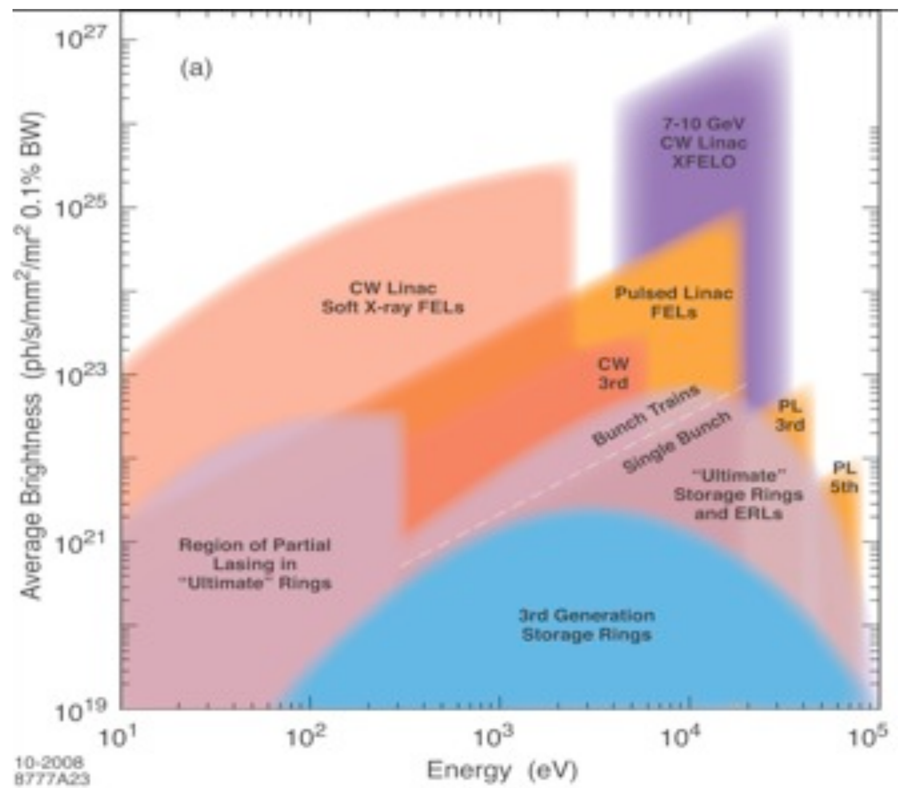
Coherent fraction:

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

SLAC NATIONAL ACCELERATOR LABORATORY

Spectral Brightness





SLAC NATIONAL ACCELERATOR LABORATORY

Comparative Light Source Performance

Comparative Light Source Performance

FELs

Comparative Light Source Performance

FELs

rings

SLAC
NATIONAL ACCELERATOR LABORATORY

What Do SR Users Care About?

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…..

SLAC NATIONAL ACCELERATOR LABORATORY

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"

What Do SR Users Care About?

Some user answers:

A lot of photons into a small spot
A lot of coherent photons
A lot of photons in a short pulse
A high pulse repetition rate
Not too many photons
Femtosecond pump-probe timing stability
50 keV photons
10^{-6} energy bandwidth (meV)
fast switched polarization

A lot of photons into a large area
A high coherent fraction
A lot of photons in a long pulse
A low pulse repetition rate
nm spatial resolution
0.1% intensity stability
280 eV photons
10^{-2} energy bandwidth
etc…..

Paraphrased:

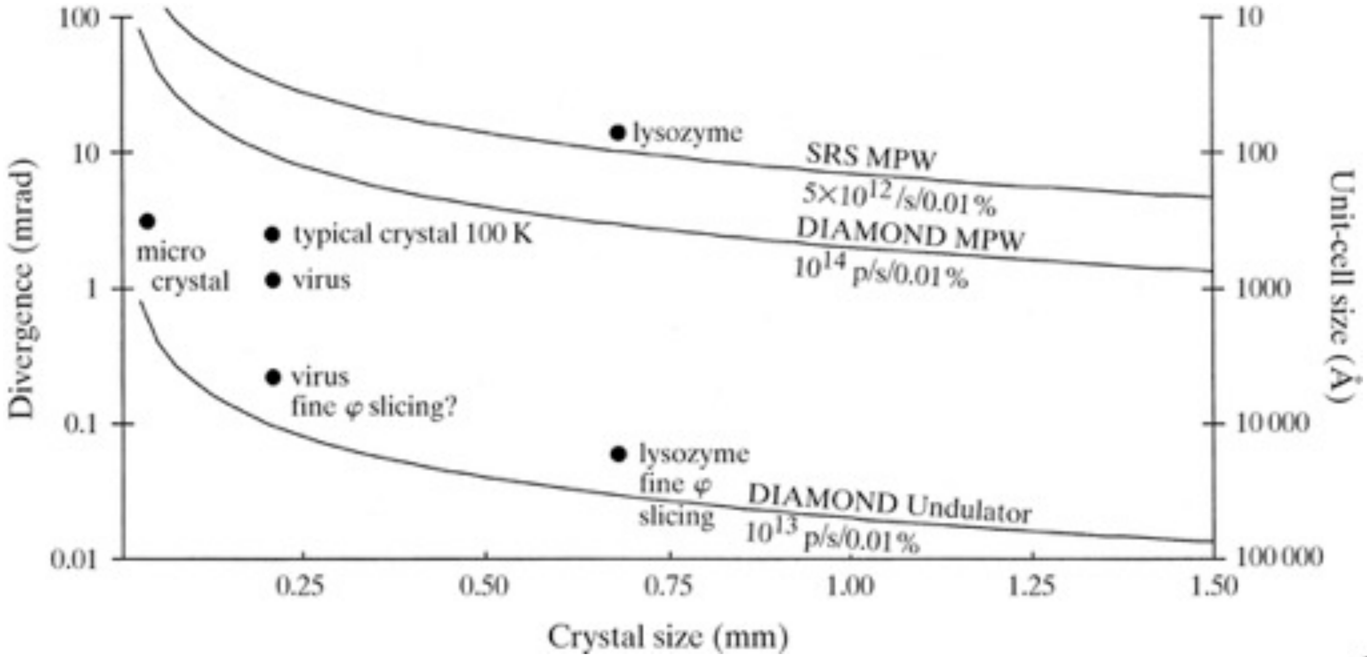
Maximum number of “usable” photons for an experiment in a minimum time

experiment = experiment “acceptance phase space”

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

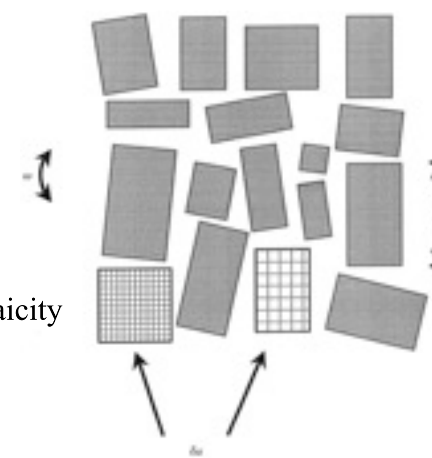
(2-/4-color mixing, nonlinear multi-photon events, non-linear multidimensional spectroscopy, etc.)

Example: Crystal Acceptance in Phase Space



C. Nave

A relatively low brightness, high flux source serves this application well



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

SLAC NATIONAL ACCELERATOR LABORATORY

December 2008

Important Parameters for Usable Photons

flux to sample

coherent flux

energy range

multiple energies (2-/4-color)

beam size

repetition rate

timing stability

bunch length

beam stability

focused flux density

photons/pulse

energy tunability

energy resolution

beam divergence

control of timing/synchronization

timing synchronization

control of bunch length

power density

etc….

Important Parameters for Usable Photons

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

etc.…

Many parameters are captured with the traditional metrics:

peak brightness | average brightness

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

Usable Photons

Usable Photons

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

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

NATIONAL ACCELERATOR LABORATORY

Usable Photons

- Photon flux 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 Photons

- Photon flux 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.

Usable Photons

- Photon flux 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

Fourier Transform Limits to Performance

Fourier Transform Limits to Performance

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:

$$\varepsilon_{diff}(\lambda) = \frac{\lambda}{4\pi} \qquad \text{(= 8 pm-rad @ 1 Å)}$$

SLAC NATIONAL ACCELERATOR LABORATORY

Fourier Transform Limits to Performance

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:

$$\varepsilon_{diff}(\lambda) = \frac{\lambda}{4\pi} \qquad \text{(= 8 pm-rad @ 1 Å)}$$

Time-energy transform limit:

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

For Gaussian pulse intensity:

$$\Delta t \times \Delta E_{ph} = \frac{h}{4\pi} \qquad (= 3.3\text{x}10^{-4}\ \text{ps(rms) eV(rms)})$$

Fourier Transform Limits to Performance

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:

$$\varepsilon_{diff}(\lambda) = \frac{\lambda}{4\pi} \qquad \text{(= 8 pm-rad @ 1 Å)}$$

Time-energy transform limit:

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

For Gaussian pulse intensity:

$$\Delta t \times \Delta E_{ph} = \frac{h}{4\pi} \qquad (= 3.3\text{x}10^{-4}\ \text{ps(rms) eV(rms)})$$

In terms of fractional bandwidth: $\frac{\Delta E_{ph}}{E_{ph}} = \frac{h}{4\pi E_{ph} \Delta t} = \frac{\lambda}{4\pi c}$

Redefined Brightness ?

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

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}:

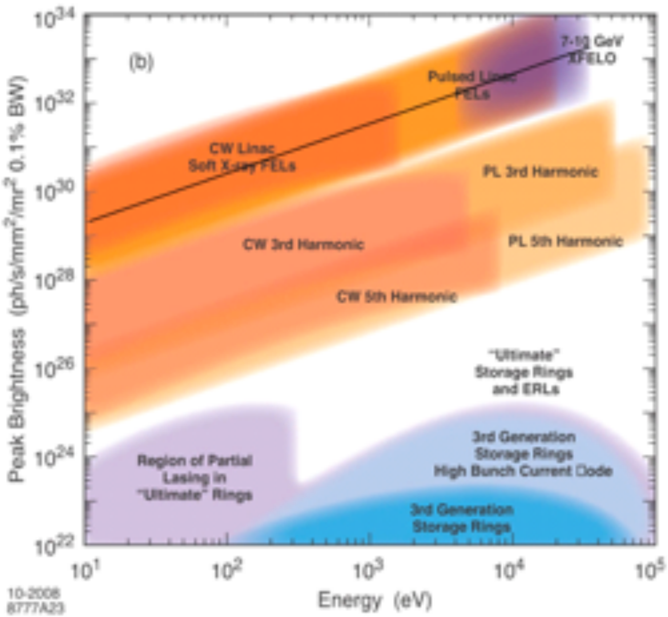
$$B_{pk}(\lambda) = \frac{N_{ph}(\lambda)}{V_{coh}(\lambda)}$$

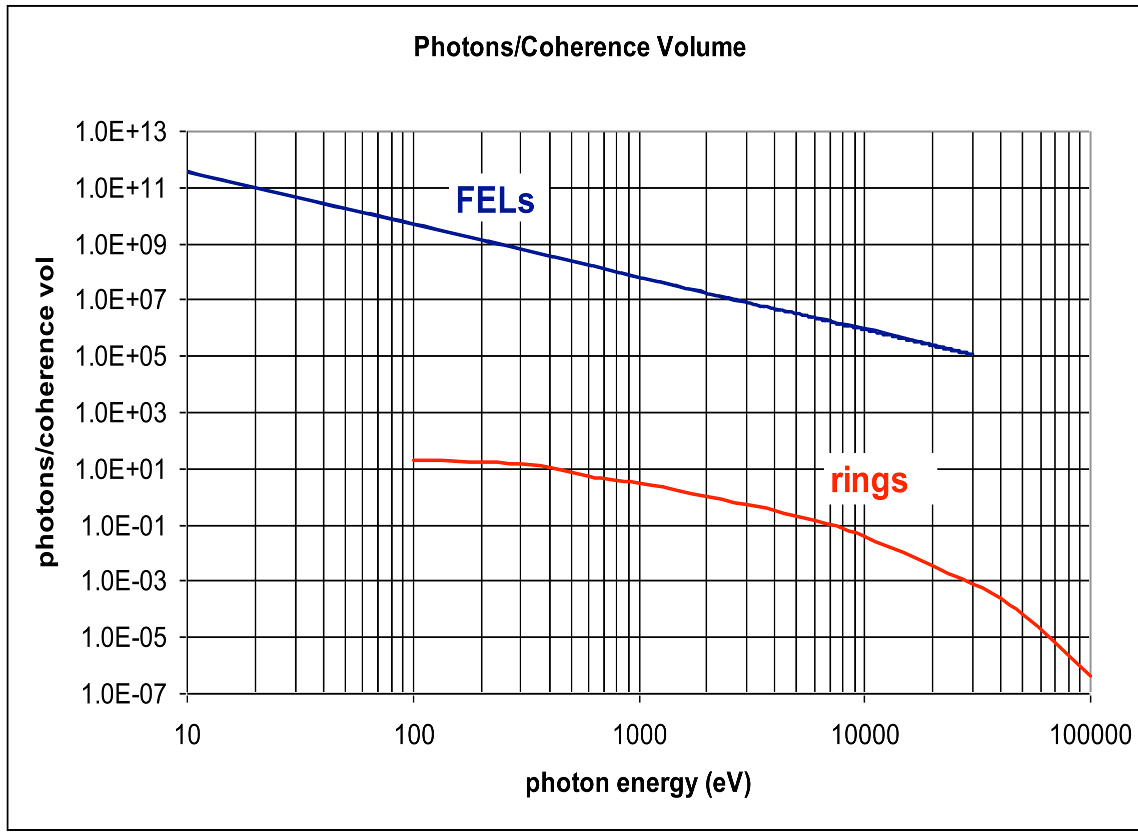
$$V_{coh}(\lambda) \sim \frac{\lambda}{4\pi} \times \frac{\lambda}{4\pi} \times \frac{\lambda}{c4\pi} = \frac{1}{c}\left(\frac{\lambda}{4\pi}\right)^3$$

$V_{coh}(1Å) = 1.17 \times 10^{-27}$ s·mm²·mrad²·0.1% BW

SLAC NATIONAL ACCELERATOR LABORATORY

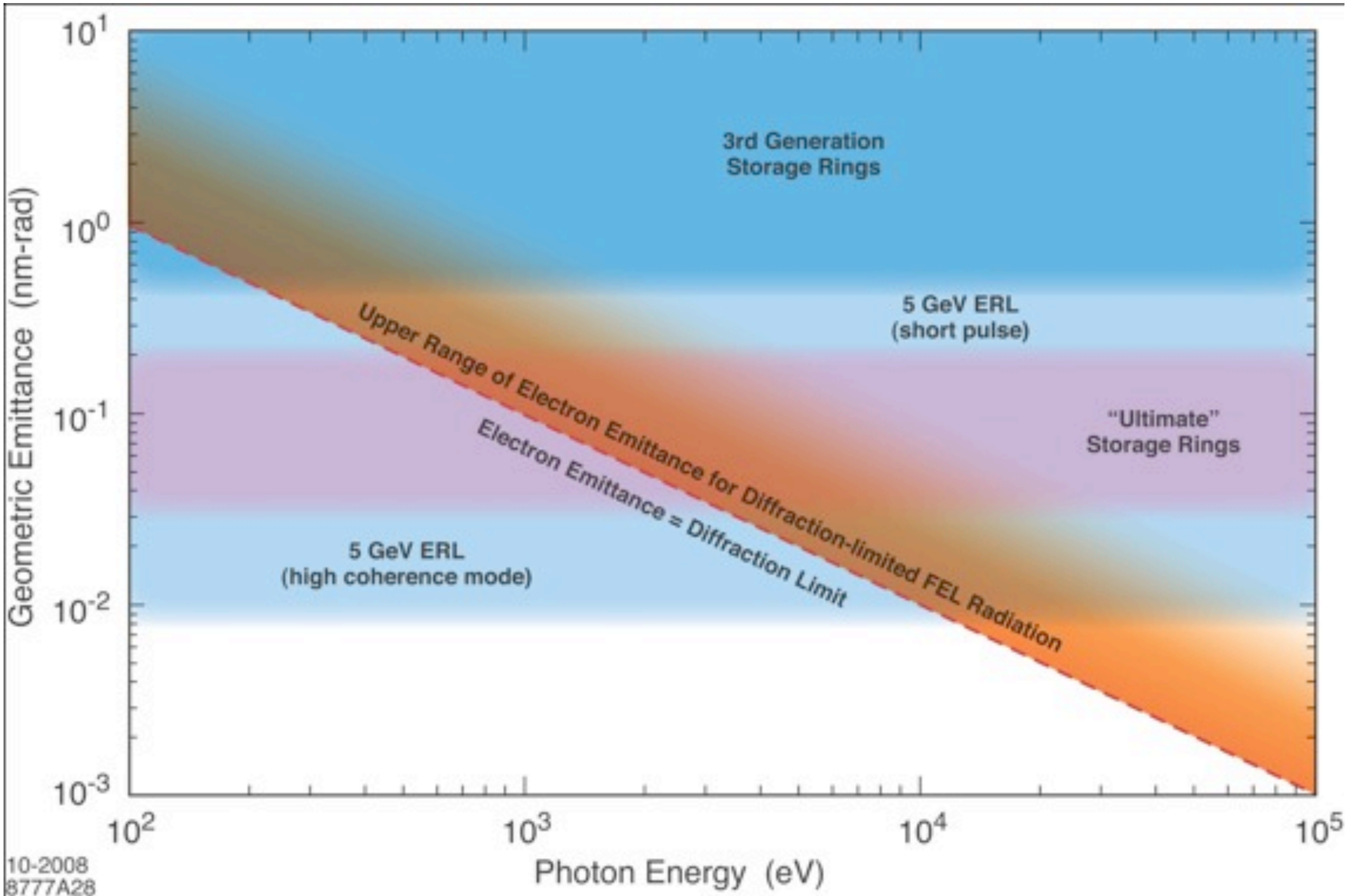
Photons per "Coherence Volume"





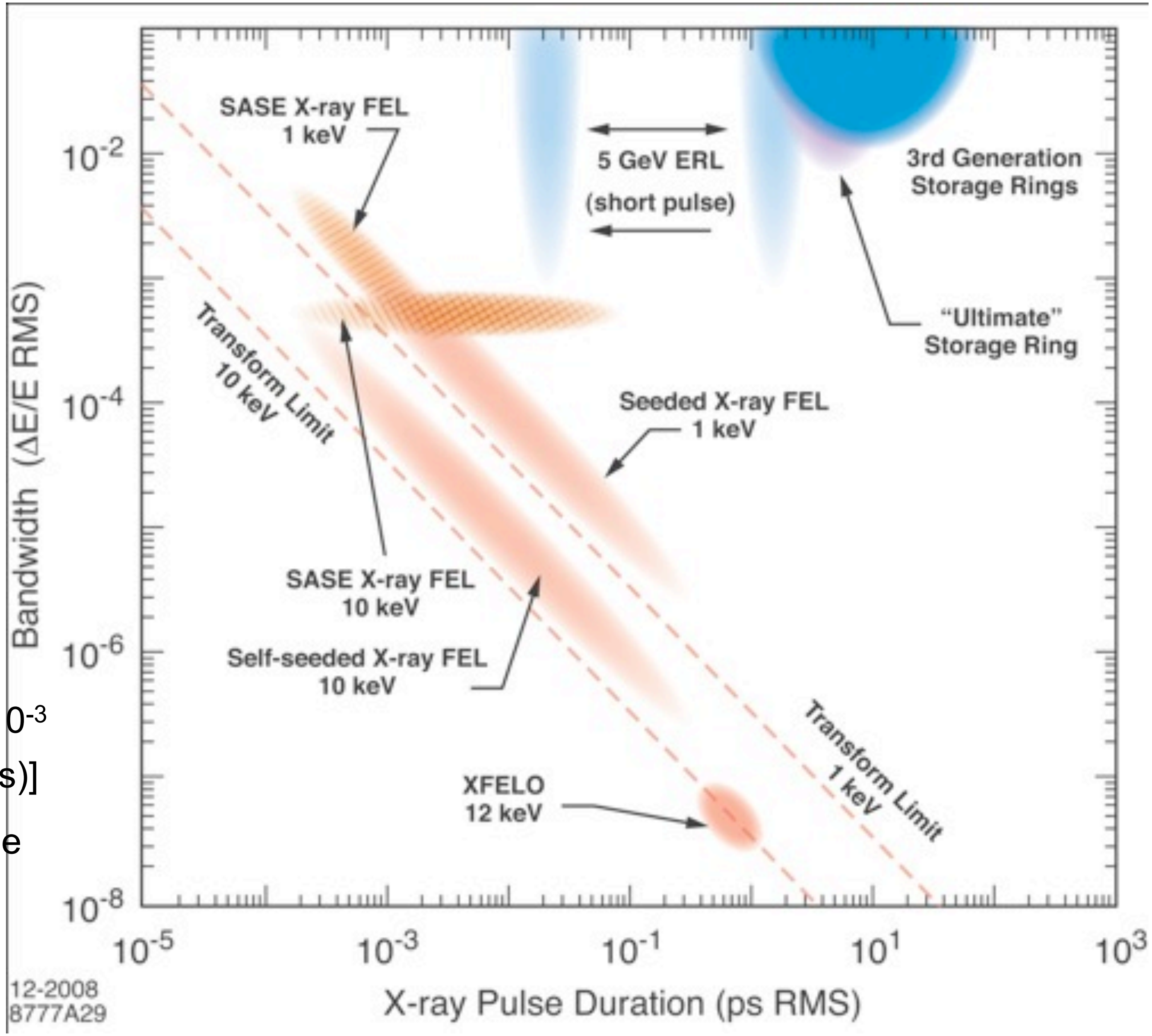
SLAC
NATIONAL ACCELERATOR LABORATORY

Diffraction-Limited Emittance



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

Energy Bandwidth vs. Pulse Length

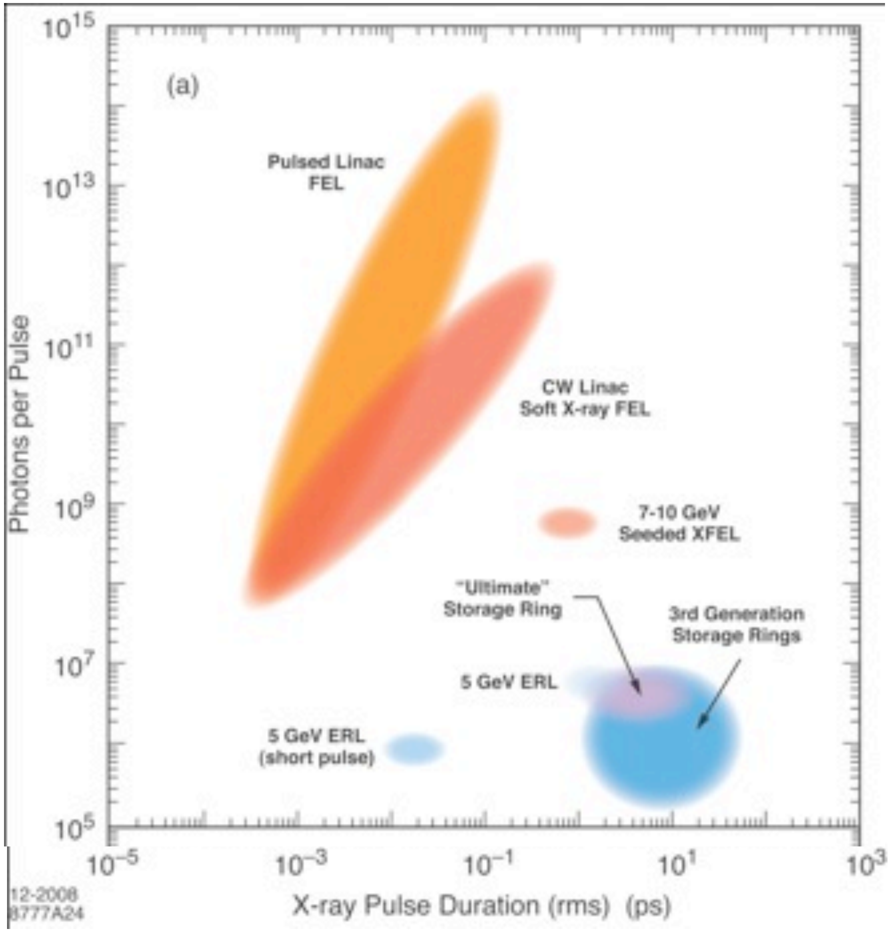


$\Delta t \cdot \Delta E = 0.33 \times 10^{-3}$

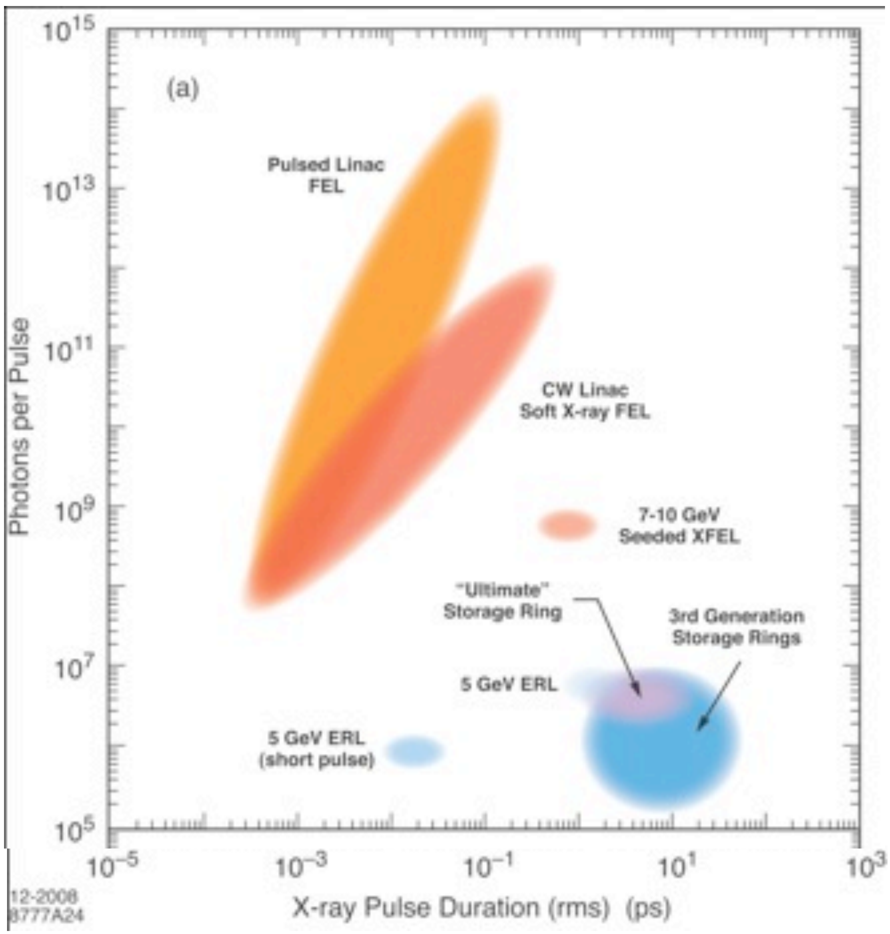
[ps(rms)·eV (rms)]

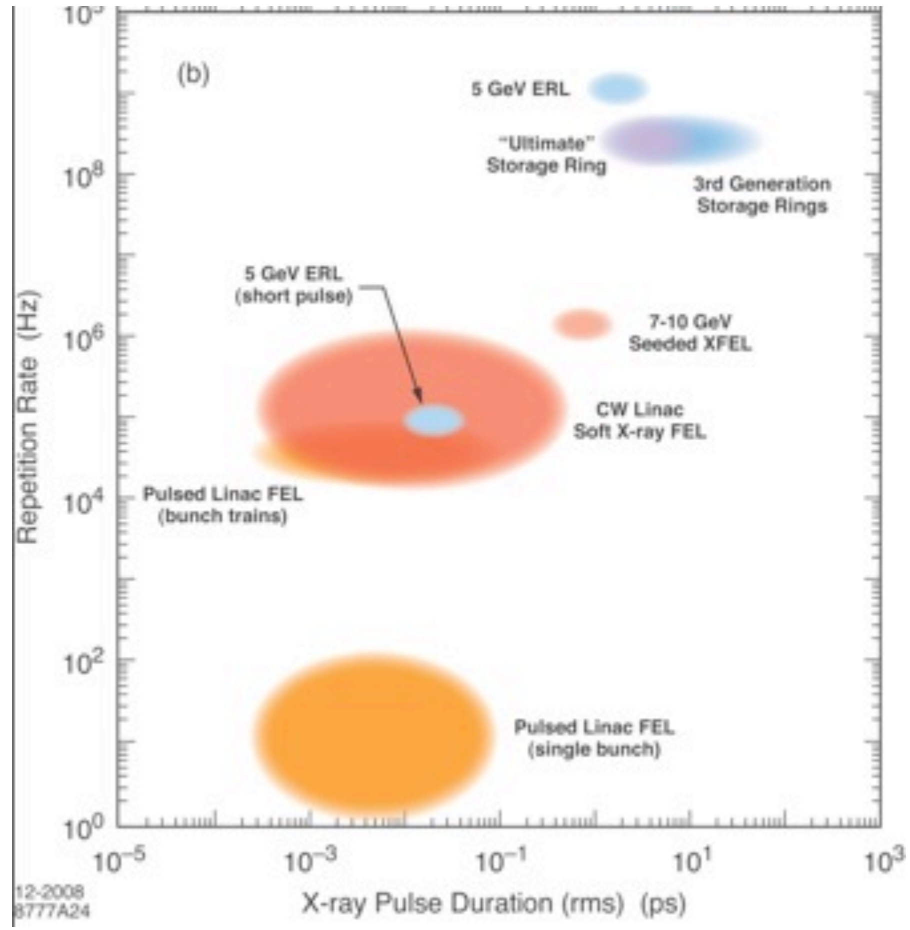
for aussian pulse

X-ray Source Temporal Performance



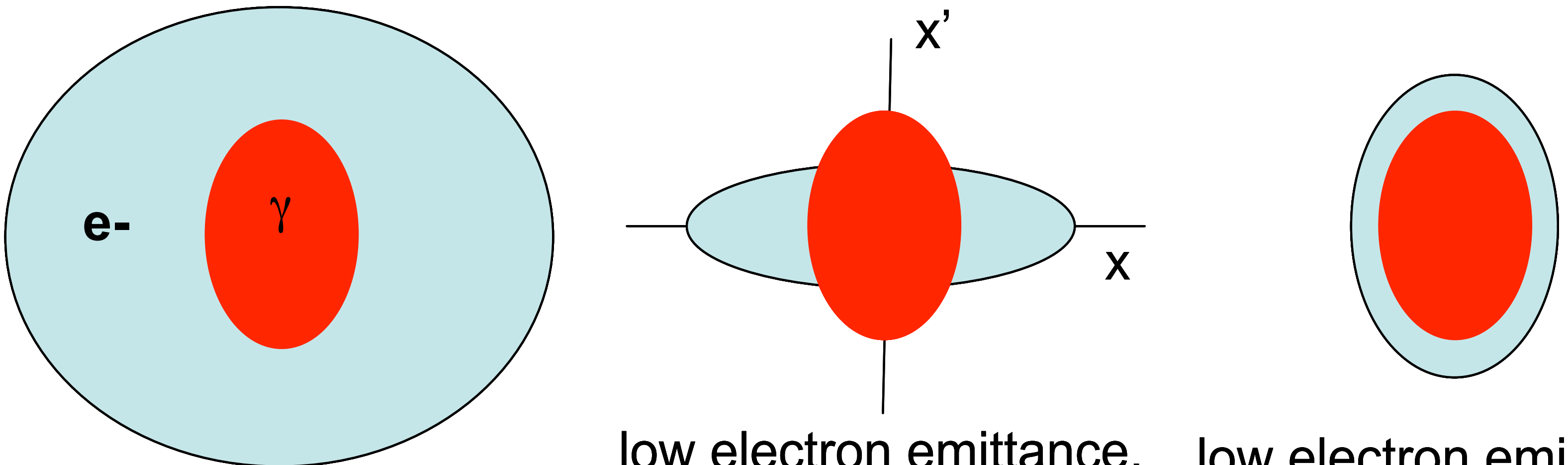
X-ray Source Temporal Performance





Limitations to Reaching Transform Limit -Transverse

Electron-photon phase space matching:



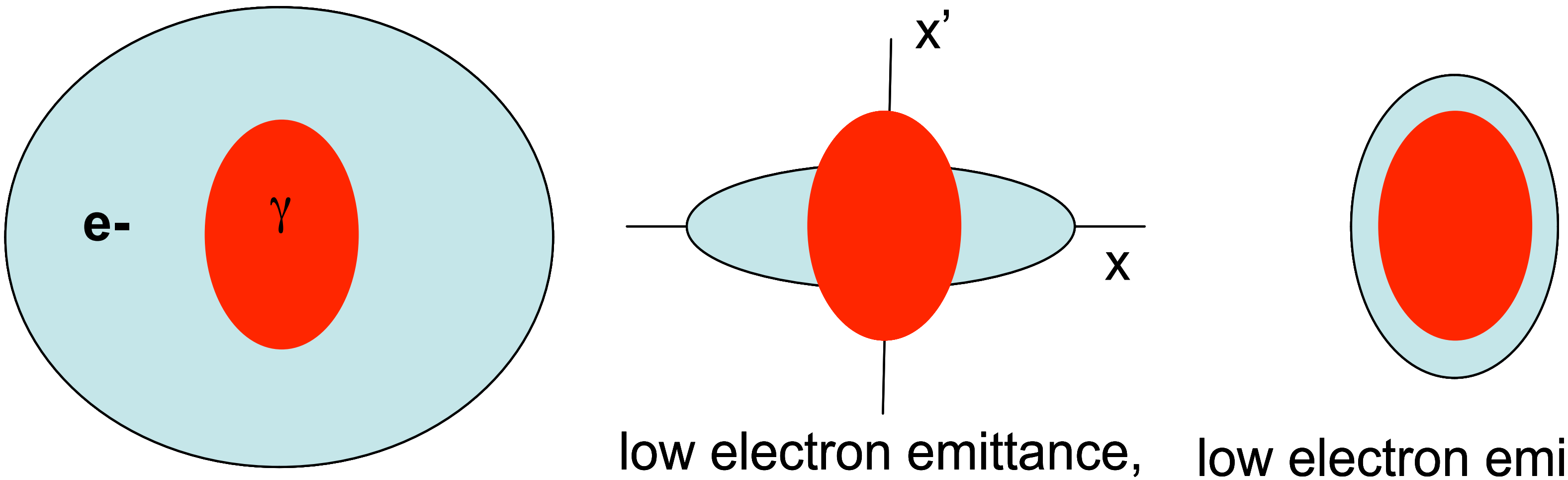
high electron emittance

low electron emittance, mismatched

low electron emittance, matched

Limitations to Reaching Transform Limit -Transverse

Electron-photon phase space matching:



high electron emittance

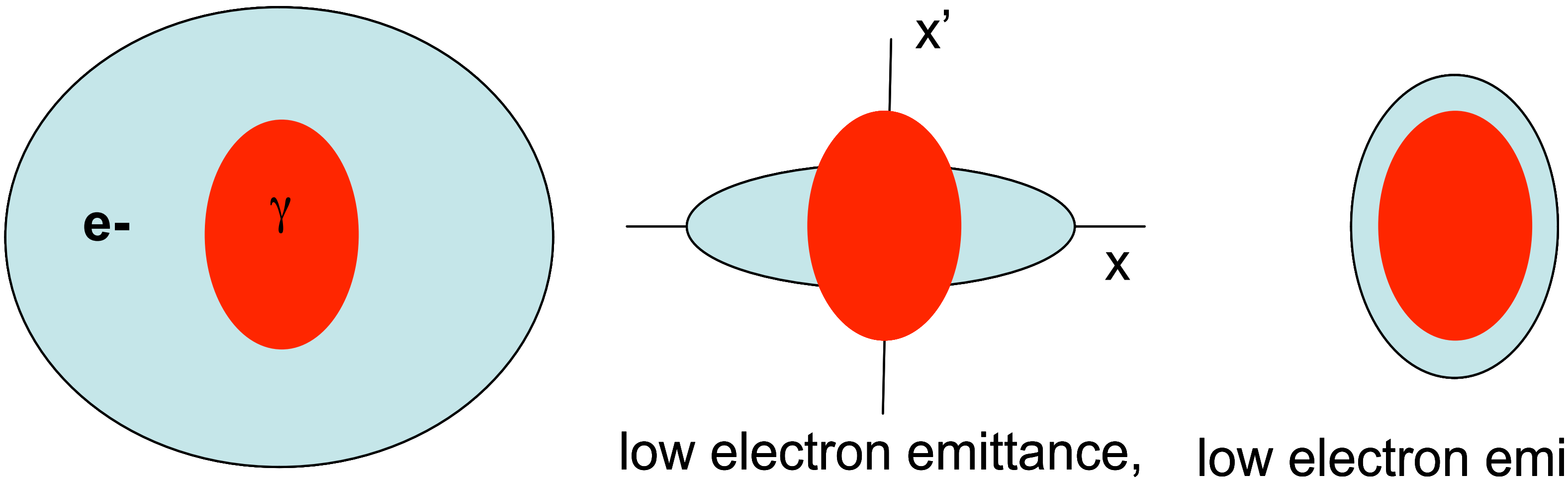
low electron emittance, mismatched

low electron emittance, matched

Insertion device parameters

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

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 #

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: σ_E = ~10^{-3} **linac/ERL: σ_E = ~10^{-4}**

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: σ_E = ~10^{-3} **linac/ERL: σ_E = ~10^{-4}**

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

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

SLAC NATIONAL ACCELERATOR LABORATORY

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
- …..

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

Other Metrics

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

polarization control

various operating modes

construction cost

etc.

timing/synchronization

simultaneous experiments

operation cost

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:

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

The Need for Complementary Light Sources

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

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

1957: Stanford representatives sign the **$114 million contract to build SLAC** with the U.S. Atomic Energy Commission. Pictured are Stanford University Trustees Morris Doyle and Ira Lillick, seated, with (left to right) Dwight Adams, university business manager; Project Director "Pief" Panofsky and Robert Minge Brown, university counsel.

Parameter	Rings	ERLs	Linac FELs
average brightness			
average flux			
peak brightness			
photons/pulse			
transverse coherence			
transverse stability			
rep rate			
control of longit phase space			
bunch length			
timing stability			
energy resolution			
energy tunability			
energy spread			
polarization control			
various operating modes			
# simultaneous experiments			

SLAC NATIONAL ACCELERATOR LABORATORY