Coherent X-Ray Sources:
Synchrotron, ERL, XFEL

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SSRL

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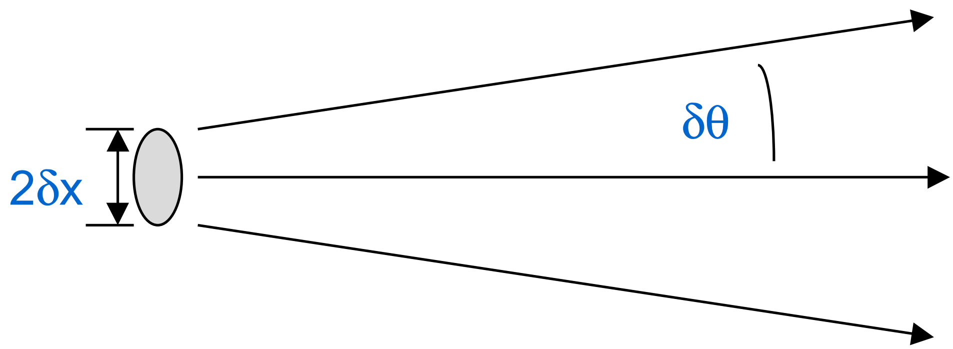
A spatially incoherent source looks coherent within an angle determined by the uncertainty principle



$$\delta x\, \delta k > 1/2$$

$$\delta k = (2\pi/\lambda)\delta\theta$$

$$d = 2\delta x \qquad \theta = 2\delta\theta$$

$$d\, \theta > \lambda/\pi$$

With source size d, there is coherence within $\theta = \lambda/\pi d$

Longitudinal (temporal) coherence is determined by the bandwidth

How long does it take for the various wavelengths to get out of phase?

The phase error is $\delta\lambda/\lambda$ per wavelength

So the temporal coherence length is $\lambda^2/\delta\lambda$

Spatial coherence of the ERL

$\lambda = 1.5$ Å d = FWHM source diameter = 100 μm

Spatial coherence within $\theta = \lambda/\pi d = 0.5$ μrad

Divergence of radiation is determined by convolution of electron beam divergence and photon divergence

electron beam div = 8 μrad FWHM

=> 9 μrad

photon div = $2/(\gamma \sqrt{n})$ = 4 μrad FWHM

The spatially coherent fraction is 0.05

Source is symmetric, so this applies to both vertical and horizontal directions

Compare to the APS (undulator A)

d = 50 μm FWHM vertical => θ = 1 μrad

Vertical electron divergence = 9 μrad FWHM
Photon divergence = 17 μrad FWHM

Total vertical divergence = 19 μrad
Vertical coherent fraction = 0.05
Similar to ERL

d = 850 μm FWHM horiz => θ = 0.06 μrad

Horizontal electron diverg = 55 μrad FWHM
Photon diverg = 17 μrad

Total horizontal divergence = 60 μrad
Horizontal coherent fraction = 0.001
Much smaller than ERL

What about APS after anticipated performance upgrades ?

Reduce horizontal emittance from 8 to 3.5 nm
Reduce emittance coupling from 1 to 0.1%
Increase undulator length from 2.4 to 4.8 m
Increase beam current from 100 to 300 mA
Assume β = 2 m

d = 6 μm FWHM vertical => θ = 8 μrad

Vertical electron divergence = 3 μrad FWHM
Photon divergence = 12 μrad FWHM
=> 12 μrad total divergence
Vertical coherent fraction = 0.7
Somewhat larger than ERL

d = 200 μm FWHM horiz => θ = 0.2 μrad

Horizontal electron diverg = 100 μrad FWHM
Photon diverg = 12 μrad
=> 100 μrad total divergence
Horizontal coherent fraction = 0.002
Much smaller than ERL

ERL is more coherent than current APS, and has some advantages over future APS

Experiments usually do not require complete spatial coherence, usually partial coherence is OK. Sometimes horizontal coherence can be sacrificed if vertical coherence is good. Depends on experiment! So comparisons are difficult.

Nevertheless, here is a comparison:

The coherent fraction of ERL radiation is at least an order of magnitude higher than the coherent fraction of the current APS undulator radiation, and is a factor of 2 higher than even a future APS source

ERL emittance is similar in vertical and horizontal. This makes for a more uniformly coherent beam

And ERL produces more flux than APS (10 times more than current APS, 2 times more than future APS). This is due to the use of a longer undulator.

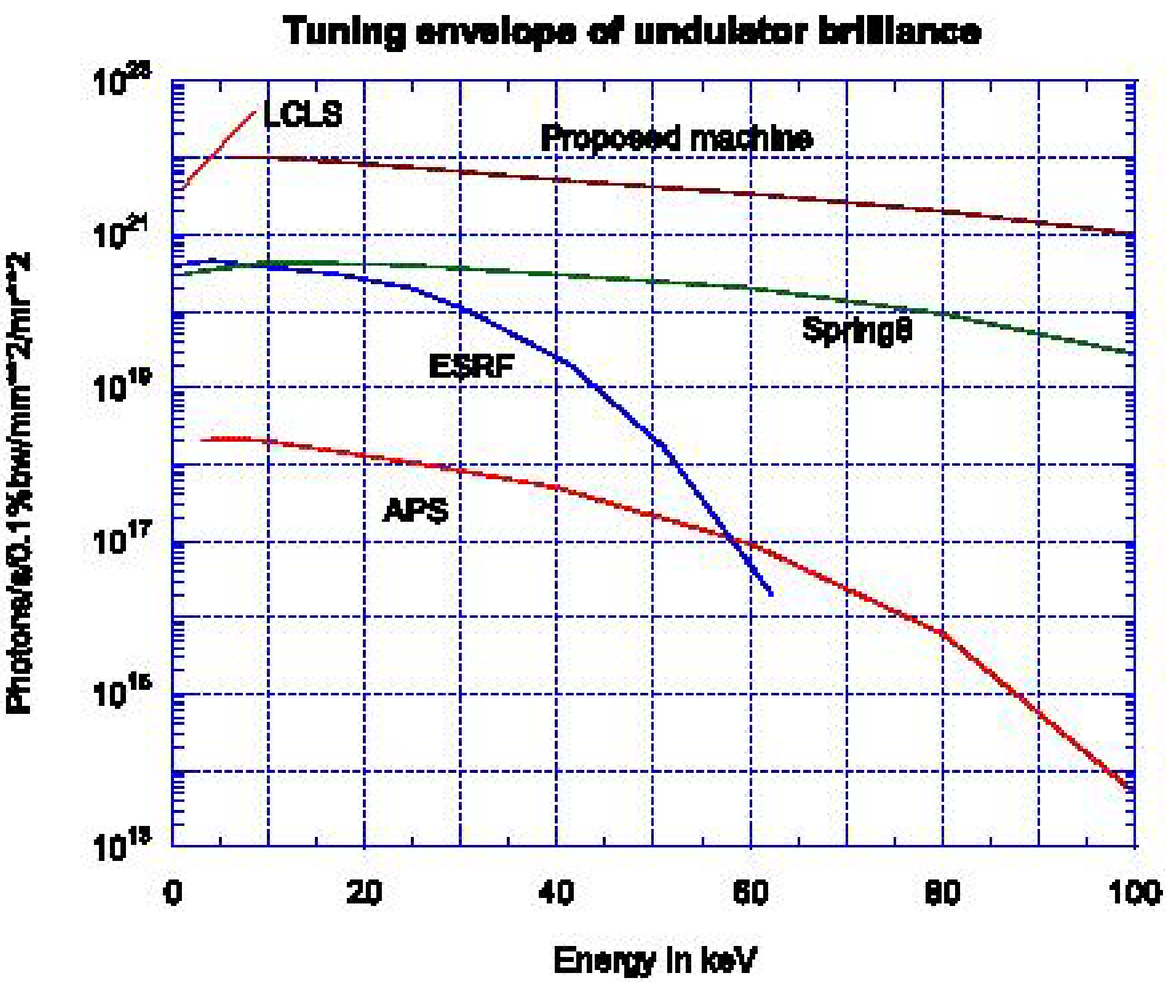
So ERL will produce 1 - 2 orders of magnitude more coherent flux than a 3rd-generation source

The comparison is even more favorable to ERL at higher energies

How do x-rayFELs compare?

Compare the electron density in phase space

	ERL	APS	LCLS
Charge/pulse	0.08 nC	15 nC	1 nC
Pulse dimensions	100 μm diam x 900 μm	50 μm x 850 μm x 22000 μm	80 μm diam x 70 μm
Electron density	70/μm^3	100/μm^3	20000/μm^3
Linear electron density	**50/Å**	**400/Å**	**10^5/Å**


Tuning envelope of undulator brilliance
Photons/s/0.1%bw/mm**2/mr**2
10^{23}
10^{21}
10^{19}
10^{17}
10^{15}
10^{13}
LCLS
Proposed machine
Spring8
ESRF
APS
0
20
40
60
80
100
Energy in keV

Synchrotron radiation *vs*. FEL radiation

The difference is in the electron beam quality

Conventional synchrotron radiation

Electron brightness << diffraction limit of emitted radiation

Electromagnetic field effects on the electrons are not significant

Each electron radiates independently, not coherently with others

Free Electron Laser radiation

Electron brightness ~ diffraction limit of radiation

EM field can cause microbunching of electrons, on scale of radiation wavelength

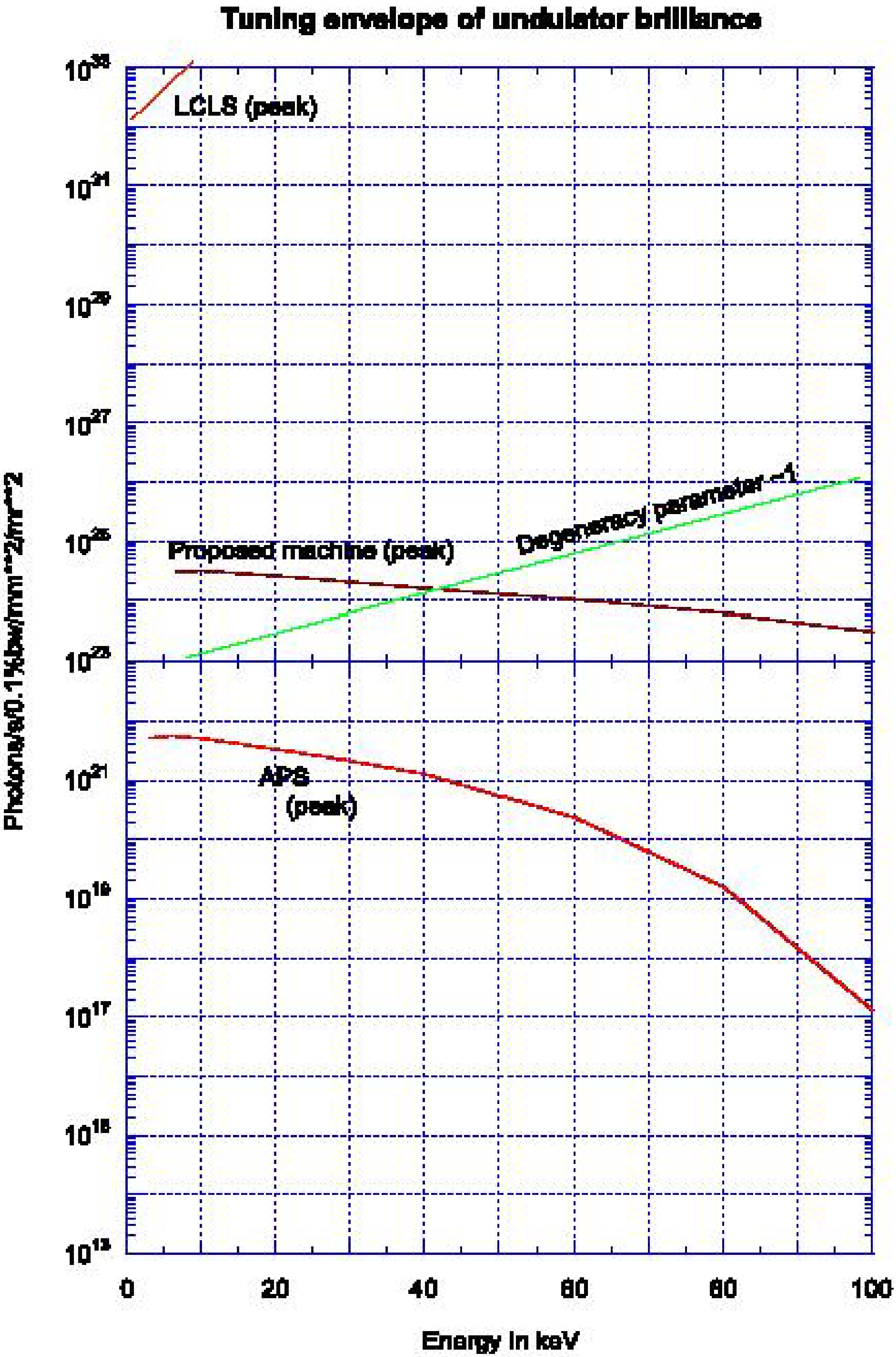
Electrons radiate collectively, coherently

Compare the photon phase space density

(1.5 Å)	ERL	APS	LCLS
Photons/ pulse	10^7	10^8	10^{12}
Photons/ coherence volume	20	0.03	10^9

Number of photons/coherence volume = degeneracy parameter

If the degeneracy parameter is > 1, thenmultiphoton coherence is possible -- nonlinear x-ray optics


Tuning envelope of undulator brilliance
LCLS (peak)
Degeneracy parameter =1
Proposed machine (peak)
APS
(peak)
10^{33}
10^{31}
10^{29}
10^{27}
10^{25}
10^{23}
10^{21}
10^{19}
10^{17}
10^{15}
10^{13}
Photons/s/0.1%bw/mm**2/mr**2
0
20
40
60
80
100
Energy in keV

Conclusions

ERL has greater spatial coherence than a 3rd-generation synchrotron, and it produces more flux

The increase in coherent flux should be 1-2 orders of magnitude at 1.5Å, and even more at shorter wavelengths

High-energy coherent x-ray experiments should be possible -- up to 50 keV or more.

A better electron gun could reduce the electron divergence, which would increase the spatial coherence. But the photon divergence would become dominant, preventing further increases

The ERL will probably never be diffraction-limited at 1.5Å, but with a good electron gun it could be diffraction-limited at 4 Å

The ERL is not a laser, but still could produce enough coherence to allow some non-linear x-ray interactions to be observed