Coherent X-Ray Sources: Synchrotron, ERL, XFEL

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

\[ \delta x \delta k > 1/2 \]

\[ \delta k = \left(\frac{2\pi}{\lambda}\right)\delta \theta \]

\[ d = 2\delta x \quad \theta = 2\delta \theta \]

\[ d \theta > \frac{\lambda}{\pi} \]

With source size \( d \), there is coherence within \( \theta = \frac{\lambda}{\pi d} \)
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**

\[ \lambda = 1.5 \ \text{Å} \quad d = \text{FWHM source diameter} = 100 \ \mu\text{m} \]

Spatial coherence within \( \theta = \frac{\lambda}{\pi d} = 0.5 \ \mu\text{rad} \)

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

- Electron beam div = 8 \( \mu\text{rad} \) FWHM
- Photon div = \( \frac{2}{\gamma \sqrt{\hbar}} = 4 \ \mu\text{rad} \) FWHM

\[ \Rightarrow \ 9 \ \mu\text{rad} \]

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 => $\theta = 1$ 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 => $\theta = 0.06$ 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 $\beta = 2$ m

$d = 6 \, \mu m$ FWHM vertical $\Rightarrow \theta = 8 \, \mu rad$

- Vertical electron divergence = $3 \, \mu rad$ FWHM
- Photon divergence = $12 \, \mu rad$ FWHM
- $12 \, \mu rad$ total divergence
- Vertical coherent fraction = 0.7
- Somewhat larger than ERL

$d = 200 \, \mu m$ FWHM horiz $\Rightarrow \theta = 0.2 \, \mu rad$

- Horizontal electron diverg = $100 \, \mu rad$ FWHM
- Photon diverg = $12 \, \mu rad$
- $100 \, \mu rad$ 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-ray FELs compare?

Compare the electron density in phase space

<table>
<thead>
<tr>
<th></th>
<th>ERL</th>
<th>APS</th>
<th>LCLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge/pulse</td>
<td>0.08 nC</td>
<td>15 nC</td>
<td>1 nC</td>
</tr>
<tr>
<td>Pulse dimensions</td>
<td>100 µm</td>
<td>50 µm x 850 µm</td>
<td>80 µm 70 µm</td>
</tr>
<tr>
<td></td>
<td>diam x 900 µm</td>
<td>850 µm x 22000 µm</td>
<td></td>
</tr>
<tr>
<td>Electron density</td>
<td>70/µm³</td>
<td>100/µm³</td>
<td>20000/µm³</td>
</tr>
<tr>
<td>Linear electron density</td>
<td>50/Å</td>
<td>400/Å</td>
<td>$10^5$/Å</td>
</tr>
</tbody>
</table>
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 $\sim$ 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

<table>
<thead>
<tr>
<th>(1.5 Å)</th>
<th>ERL</th>
<th>APS</th>
<th>LCLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons/pulse</td>
<td>$10^7$</td>
<td>$10^8$</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>Photons/coherence volume</td>
<td>20</td>
<td>0.03</td>
<td>$10^9$</td>
</tr>
</tbody>
</table>

Number of photons/coherence volume = degeneracy parameter

If the degeneracy parameter is > 1, thermultiphoton coherence is possible -- nonlinear x-ray optics
Tuning envelope of undulator brilliance

- LCLS (peak)
- Proposed machine (peak)
- APS (peak)
- Degeneracy parameter -1

Energy in keV

Photons/eV x 1/kW/m/sr/2mm²
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.