Free Electron Laser

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Outline

• What is FEL
• Why X-ray FEL
• Why ultrafast
• Future prospects of FEL
What is laser

Light Amplified by Stimulated Emission of Radiation
Conventional gain medium
Coherence

• Spatial coherence:
  make the light stay collimated for a long distance
  focus the light to a tight point

• Temporal coherence
  emit light with a very narrow spectrum
What is free electron laser

\[ \lambda \propto \frac{\lambda_u}{\gamma^2} \]
Microbunching

Diagram showing different stages of microbunching:

- a) Initial state with electrons evenly distributed.
- b) Beginning of bunching with some electrons gaining relative phase.
- c) Further development of bunching with increased phase difference.
- d) Fully bunched state with electrons closely aligned.

Text:
- Incoherent emission: electrons randomly phased
- Coherent emission: electrons bunched at radiation wavelength
Microbunching

1. Spontaneous emission
2. Modulation, exponential gain
3. Bunching, coherent emission
4. Overbunching, saturation

Length along undulator

Log(radiated power)

Beam dump

$10^6 - 10^9$
Microbunching
Laser seeding

The injection of a seed laser in a free-electron laser (FEL) amplifier reduces the saturation length and improves the longitudinal coherence.
Put the undulator in an optical cavity
Space Charge effect
Energy recovery linac (ERL)

Re-use the electrons to save energy
3.4 km Xray-FEL in Europe
LCLS in SLAC
LCLS in SLAC
## Comparison

<table>
<thead>
<tr>
<th>Conventional laser</th>
<th>Free Electron Laser</th>
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<tbody>
<tr>
<td>Bond states</td>
<td>Free electrons</td>
</tr>
<tr>
<td>Gain medium</td>
<td>No gain medium</td>
</tr>
<tr>
<td>Limited frequency range</td>
<td>Wide frequency range</td>
</tr>
<tr>
<td>cheap</td>
<td>Very expensive</td>
</tr>
<tr>
<td>High efficiency (up to 30%)</td>
<td>low efficiency (~0.1%)</td>
</tr>
<tr>
<td>Small size (even on chip)</td>
<td>Large facility (~km)</td>
</tr>
<tr>
<td>More coherent</td>
<td>Less coherent</td>
</tr>
</tbody>
</table>
People Prefer to build X-ray FEL

coherent X-ray radiation: research into dense plasmas (not transparent to visible radiation), phase-resolved medical imaging, material surface research
Why X-ray laser difficult

- An optical cavity is no longer possible for wavelengths below 100 nm
Why X-ray laser difficult

- Short lifetime of excited state
- High Pumping energy for population inversion
It is easier to build X-ray FEL

\[ \lambda \propto \frac{\lambda_u}{\gamma^2} \]
<table>
<thead>
<tr>
<th>X-FEL facility</th>
<th>Pulse duration (fs)</th>
</tr>
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<tbody>
<tr>
<td>LCLS</td>
<td>5-250</td>
</tr>
<tr>
<td>SACLA</td>
<td>4.3</td>
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<tr>
<td>European X-FEL</td>
<td>1.68-107</td>
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<tr>
<td>Korean X-FEL</td>
<td>8.6-26</td>
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<tr>
<td>Swiss X-FEL</td>
<td>2-20</td>
</tr>
<tr>
<td>FLASH</td>
<td>15-100</td>
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<tr>
<td>Fermi</td>
<td>&lt;40</td>
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</tbody>
</table>

![Graph showing pulse width FWHM and peak power](image-url)
Why ultrafast

Electronics

Protein Folding
Kinetics

Ultrashort Laser Pulses
Rotation
Vibration
Liquid Dynamics
Electron Dynamics

Radiative Decay
Vibrational Relaxation

Range: $1 \rightarrow 10^{-18}$ s
Potential for bright attosecond laser

(1) Pulse cannot be shorter than a wavelength atomic unit of time: 24 as

\[ \lambda = cT = 7.2 \text{ nm} \]

(2) Time-bandwidth product:

\[ \Delta t \Delta w \sim 1 \quad \Rightarrow \quad \Delta w \sim 4 \text{ PHz} \]
Potential for bright attosecond laser

• Need very tight electron beam
  (1) Reduce the charge of single beam to < 1 pC (nC level for femtosecond FEL)
  (2) Modulate the beam, allowing only a short section of the electrons to emit radiation
Gamma-ray laser?

- Too big photon, recoiling electrons, leading to instability of electron beam
- Quantum diffusion:

\[ D \propto \gamma^4 \]
Higher harmonic in FEL

(a) Broadband synchrotron radiation

- Harmonic bandwidth $\sim 1/nN_u$
- Fundamental bandwidth $\sim 1/N_u$

(b) Undulator radiation

- $E_x$
- $\lambda_u$
- $e^-$
Compact FEL

• Can we build a FEL with size of < 10 m?

Reference

[12] Sverker Werin, Tutorial on FEL
[13] Peter Schmuser, Free electron lasers