Feasibility Study of Short-Wavelength and High-Gain FELs in an Ultimate Storage Ring

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- Ultimate Storage Ring
- Analysis
- Simulation
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3rd Generation Light Source
- Storage ring
- Average brightness $B_0 \sim 10^{20}\text{ (ph/s/mrad2/mm2/0.1\%bw)}$

4th Generation Light Source
- Linac
- Average brightness $B_x \sim 10^{26}\text{ (ph/s/mrad2/mm2/0.1\%bw)}$

Storage-Ring-Based Light Sources finished?
- stability, reliability, variety of bunch pattern, many photon beam line, matured technology
- Ultimate storage ring
  Average brightness $B_u \sim 10^{23}\text{ (ph/s/mrad2/mm2/0.1\%bw)}$
  $\sim (10^2-10^3)B_0$

Objective
- To increase the average brightness of an ultimate storage ring to $10^4-10^6B_0$
Introduction

Partial Lasing
• Z. Huang et al\textsuperscript{1} showed that short-wavelength high-gain FEL is possible in PEPX storage ring
  • $\lambda=3.3\text{ nm-30 nm}$
  • Average Brightness $10^2-10^3B_0$

Wavelength Region
• Is shorter wavelength FEL in storage ring impossible?

The approximate range of average brightness.\textsuperscript{2}

\textsuperscript{1} Z. Huang et al., Nucl. Instr. and Meth. A 593 (2008) 120.
\textsuperscript{2} J. Corlett and R. Hettel, PAC09.
# Ultimate Storage Ring

## Main Parameters of Storage Ring

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>$E$</td>
<td>6 GeV</td>
</tr>
<tr>
<td>Natural emittance</td>
<td>$\varepsilon_o$</td>
<td>34.5 pm</td>
</tr>
<tr>
<td>Full coupling</td>
<td>$\varepsilon_{x,y}$</td>
<td>17.3 pm</td>
</tr>
<tr>
<td>Normalized</td>
<td>$\gamma \varepsilon_{x,y}$</td>
<td>0.20 um</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$\sigma_e$</td>
<td>0.89x10^{-3}</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_l$</td>
<td>1.23 mm</td>
</tr>
<tr>
<td>Circumference</td>
<td>$L_c$</td>
<td>1999 m</td>
</tr>
<tr>
<td>Lattice</td>
<td></td>
<td>10 bend achromat</td>
</tr>
<tr>
<td>Number of cells</td>
<td>$N_c$</td>
<td>32</td>
</tr>
</tbody>
</table>

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Ultimate Storage Ring – Betatron function and dynamic aperture

Betatron and dispersion functions in a cell

- Dynamic aperture is small, but enough to store the beam.
- Long straight section length is 6 m and $\beta_x=25\text{m}$, $\beta_y=5\text{m}$.
- But it is easy to change the straight section length without changing the main parameters.
Effect of intrabeam scattering at 1mA bunch current

- Emittance growth at 100% coupling
  \[ \varepsilon_x = \varepsilon_y = 17 \text{ pm} \]
  \[ \varepsilon_x = \varepsilon_y = 37 \text{ pm} \]
- Bunch lengthening
  Negligibly small

Emittance in an actual machine

- Emittance \( \varepsilon_x = \varepsilon_y < 37 \text{ pm} \)
- Damping effect of undulator
- Use of damping wiggler
Analysis

- Analisis was done as follows.¹

Energy spread in a storage ring

Rate-of-change of energy spread

\[
\frac{d\sigma^2}{dt} = \frac{\sigma^2}{\tau_e} - \frac{\sigma^2}{\tau_e} + \frac{2P}{\rho P_{\text{beam}} T_0}
\]

\[
\sigma_0 = \sigma_{e_0} / \rho, \sigma = \sigma_e / \rho
\]

- Solving these equations numerically for \( \sigma_e \), energy spread \( \sigma_e \), FEL power \( P \), and power gain length \( L_g \) are obtained.

FEL Power

\[
P \approx P_n \exp\left(\frac{Z}{L_G}\right)
\]

\[
L_G = L_{G0} (1 + \Lambda)
\]

\[
\Lambda(\sigma_e, \varepsilon, \beta, \ldots)^2
\]

\[
\rho = \left[ \frac{1}{8\pi I_A} \left( \frac{K[JJ]}{1 + K^2 / 2} \right) \frac{\gamma^2 \lambda_r^2}{\Sigma_x} \right]^{1/3} 
\]

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¹ Z. Huang et al., Nucl. Instr. and Meth. A 593 (2008) 120.
In the calculation, the following undulators are assumed.

### Undulator Parameters

<table>
<thead>
<tr>
<th>$\lambda_r$</th>
<th>$\lambda_u$</th>
<th>$K$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10 nm</td>
<td>15 mm</td>
<td>1.3</td>
<td>SPring-8 XFEL$^1$</td>
</tr>
<tr>
<td>0.18 nm</td>
<td>18 mm</td>
<td>1.9</td>
<td>SPring-8 XFEL$^1$</td>
</tr>
<tr>
<td>0.49 nm</td>
<td>37 mm</td>
<td>2.3</td>
<td>SPring-8 storage ring$^2$</td>
</tr>
<tr>
<td>0.90 nm</td>
<td>45 mm</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>1.86 nm</td>
<td>50 mm</td>
<td>4.3</td>
<td>PEP-X$^3$</td>
</tr>
</tbody>
</table>

Analysis – Beta dependence of FEL power

- Assumption: Undulator length 100 m, Bunch current $1\text{mA}$ ($I_0 = 648A$)
- For 17 pm emittance, $2\text{ m} < \beta < 4\text{ m}$ and for 37 pm, $2\text{ m} < \beta < 5\text{ m}$.

(a) $\varepsilon_x = \varepsilon_y = 17\text{ pm}$

(b) $\varepsilon_x = \varepsilon_y = 37\text{ pm}$
Analysis – Betatron function at undulator section

- FODO cell was chosen as the lattice in the undulator section
- Betatron function should be less than 5 m.
- The shorter the cell length, the smaller the average betatron function.
  But, the undulator’s occupation ratio in the undulator section becomes small.
- 3.5 m cell length is determined. Average betatron function value became 6.7 m.

(a) FODO cell  
(b) Betatron function
Analitical Results

Undulator length dependence of power, energy spread, gain length at $\varepsilon_x=\varepsilon_y=17\text{pm}$

- Achievable maximum power in the storage ring is $\sim 1 \text{ MW}$.
- Increase of FEL power: Increase of FEL Interaction $\longrightarrow$ Increase of energy spread $\longrightarrow$ Degradation of gain length $\longrightarrow$ Saturation of FEL power

(a) Undulator length dependence of FEL power

(b) Undulator length dependence of energy spread

(c) Undulator length dependence of gain length

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Analitical Results
Undulator length dependence of power, energy spread, gain length at $\varepsilon_x=\varepsilon_y=37\text{pm}$

- Achievable maximum FEL power is $\sim 1\text{ MW}$.

(a) Undulator length dependence of FEL power  
(b) Undulator length dependence of energy spread  
(c) Undulator length dependence of gain length
Simulation

- Numerical simulations have been done using SIMPLEX\(^1\).
- For 1.86 nm, maximum power 400 kW (17pm) and 100 kW(37pm).
- For 0.90 nm, maximum power 70 kW (17pm) and 3 kW(37pm).
- Amplification from ~300 times to ~600 times is possible at 1.86 nm.
- At 0.90 nm, amplification from ~10 to ~100 is possible.

\[(a) \varepsilon_x = \varepsilon_y = 17 \text{ pm} \quad (b) \varepsilon_x = \varepsilon_y = 37 \text{ pm}\]

\(^1\) T. Tanaka, http://radiant.harima.riken.go.jp/simplex
Simulation

FEL with a bypass

- For a 17 pm emittance beam, we can achieve saturation at 1.86 nm and 0.9 nm.
- For a 37 pm emittance beam at 1.86 nm, FEL power nearly reached saturation.
- FEL power is about 1 GW.

(a) $\varepsilon_x = \varepsilon_y = 17$ pm

(b) $\varepsilon_x = \varepsilon_y = 37$ pm
Summary

- We studied the viability of the high-gain FELs in wavelengths ranging from 0.10 nm to 1.86 nm, assuming 1 mA bunch current in an ultimate storage ring.

- Analytical results showed that the achievable maximum FEL power in the storage ring is on the order of 1 MW.

- Assuming a 90 m effective length undulator, we carried out the simulations using SIMPLEX.
  - At 1.86 nm, the maximum achievable power is 100-400 kW and we can expect about 300-600 times power amplification.
  - At 0.90 nm, the maximum achievable power is 3-70 kW and we can expect about 6-100 times power amplification.
  - We also carried out simulations with a bypass and found that FEL saturation is possible at 1.86 nm.

- These results show that FEL in the ultimate storage ring is promising for wavelengths longer than 0.9 nm.