XFEL Oscillator in ERLs

R. Hajima
Japan Atomic Energy Agency
March 4, 2010.
X-ray FEL Oscillator

K-J. Kim et al., PRL (2008), PRST-AB (2009)

Typical electron beam parameters for XFEL Oscillator

<table>
<thead>
<tr>
<th>$\lambda_1$ (Å)</th>
<th>$E$ (GeV)</th>
<th>$Q$ (pC)</th>
<th>$K$</th>
<th>$\lambda_U$ (cm)</th>
<th>$N_U$</th>
<th>$Z_R$ (m)</th>
<th>$g_{th}$ (%)</th>
<th>$g_{sim}$ (%)</th>
<th>$r$ (%)</th>
<th>$P_{sat}$ (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>19</td>
<td>1.414</td>
<td>1.88</td>
<td>3000</td>
<td>10</td>
<td>26</td>
<td>28</td>
<td>90</td>
<td>19</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>40</td>
<td>1.414</td>
<td>1.88</td>
<td>3000</td>
<td>12</td>
<td>55</td>
<td>66</td>
<td>83</td>
<td>21</td>
</tr>
<tr>
<td>0.84</td>
<td>7.55</td>
<td>19</td>
<td>1.414</td>
<td>1.88</td>
<td>3000</td>
<td>12</td>
<td>26</td>
<td>28</td>
<td>90</td>
<td>20</td>
</tr>
<tr>
<td>0.84</td>
<td>10</td>
<td>19</td>
<td>2</td>
<td>2.2</td>
<td>2800</td>
<td>10</td>
<td>42</td>
<td>45</td>
<td>83</td>
<td>18</td>
</tr>
</tbody>
</table>

Energy, charge, emittance, repetition are similar to ERL beams.
ERL Injector Performance

*design example*

8 pC, 0.1 mm-mrad will be feasibly obtained.

500-kV DC gun, 3-D pulse shaping, and 10-MeV SCA.

- 7.7 pC
- $\sigma_x$, $\sigma_y$, $\varepsilon_x$, $\varepsilon_y$
- z (m)

80 pC, 0.1 mm-mrad will be obtained.

750-kV DC gun, 3-D pulse shaping, and 10-MeV SCA.

- R. Hajima et al.
  Compact ERL CDR (2008)

- I.V. Bazarov et al., PRST-AB (2005)
Integration of XFELO and ERL

- Location
  - straight section of the loop
  - additional branch

- Operation mode
  - independent
  - concurrent

From the ERL side,

XFELO adds a new feature with minor modification
ERL and XFELO provides complimentary X-rays
Growth of emittance and energy spread in a loop

E = 5 GeV, \( \rho = 25 \text{ m} \), “half arc” = TBA x 15

\[ I_5 = 2.3 \times 10^{-5} (m^{-1}) \]
\[ \Delta \varepsilon_x = \frac{2r_e}{3} C_q \gamma^5 I_5 = 1.4 \text{ pm} \]
\[ I_3 = 5.0 \times 10^{-3} (m^{-2}) \]
\[ \Delta \left( \frac{\sigma_p}{p} \right) = \left( \frac{2r_e C_q \gamma^5 I_3}{3} \right)^{1/2} = 1.8 \times 10^{-5} \]

coherent SR

\[ \sigma_{CSR}^E = 8 \text{ keV} \quad \text{for 20pC/2ps} \]

energy spread after FEL lasing

\[ \frac{\Delta E}{E} = \frac{1}{N_u} \sim 0.05\% \]

Energy recovery is preserved

FEL gain is preserved

\[ \Rightarrow \text{ negligible emittance growth} \]
**XFEL0 lasing at 5-GeV?**

0.1nm XFEL0 with a 5-mm gap Halbach-type undulator

7 GeV, $\lambda_w=1.88\text{cm}$, gap=5mm, $a_w=1 \rightarrow \lambda=0.1\text{nm}$

5 GeV, $\lambda_w=1.43\text{cm}$, gap=5mm, $a_w=0.59 \rightarrow \lambda=0.1\text{nm}$

1-D gain $\propto \rho^3 = \frac{1}{16\pi} a_w^2 \lambda_w^2 [JJ]^2 \frac{1}{\gamma^3 I_p} \frac{1}{\Sigma}$

$JJ = J_0(\xi) - J_1(\xi), \quad \xi = \frac{a_w^2}{2(1+a_w^2)} \quad I_A = 17\text{kA}, \quad I_p = \text{peak current}, \quad \Sigma = \text{mode area}$

assuming same peak current and same mode area,

$$\frac{\rho^3(5\text{GeV})}{\rho^3(7\text{GeV})} = 0.65$$

1-D gain for 5 GeV beam is “0.65 x 1-D gain for 7 GeV”

further gain reduction due to the emittance effect.
The above calculations are based on a Halbach-type undulator. DELTA undulator gives 1.4 times larger FEL gain.
Velocity bunching in an ERL main linac

Velocity bunching for a SASE-FEL injector  
L. Serafini and M. Ferrario, AIP-Porc. (2001)

Velocity bunching for an ERL light source  

Velocity bunching for an X-FELO  
R. Hajima, N. Nishimori, FEL-2009

(1) no additional component is required
(2) only 2-3% SCAs are used for the velocity bunching
(3) residual energy spread is smaller than magnetic compression
(4) moderate emittance growth for low bunch charge
Gain reduction by bandwidth mismatch

\[ \Lambda_m = \frac{(g - \alpha)}{2} - \left( \frac{u}{2\tau_M} \right)^2 - 0.5 \sqrt{g(2m + 1)} \left( \frac{\tau_M}{\tau_{el}} \right) \]

- growth rate of the \( m \)-th mode
- gain
- loss
- cavity length detuning
- bandwidth mismatch

K-J. Kim et al., PRL 100, 244802 (2008).

\[ \sigma^M_\omega \gg \sigma^{el}_\omega \quad \text{or} \quad \tau_M \ll \tau_{el} \]

- bandwidth of the Bragg mirrors = 12 meV
- \( \tau_M = 100 \text{ fs} \)
- \( \tau_{el} \gg 100 \text{ fs} \)

In the following calculations, we choose \( \tau_{el} = 400 \text{ fs} \)

reflectivity and phase shift for a cavity round trip

12 meV

R. Hajima
Example of the velocity bunching

PARMELA simulation

bunch charge \( q = 7.7 \text{ pC} \)

velocity bunching

bunching in 8 cavities

injection 10.9 MeV, 1.3 ps, -85 deg.

gradient \( E_{\text{acc}} = 8.5 \text{ MV/m} \)

emittance growth by chromatic aberration

\[
\begin{align*}
\sigma_x & = \text{beam size (mm)} \\
\varepsilon_x & = \text{norm. emittance (mm-mrad)} \\
\varepsilon_y & = \text{norm. emittance (mm-mrad)} \\
\end{align*}
\]
Optimum design of the velocity bunching

bunch charge $q = 7.7$ pC

velocity bunching
bunching in 6 cav. + on-crest 2 cav.
injection 10.9 MeV, 1.3 ps, -90 deg.
gradient $E_{acc} = 8.5$ MV/m

at the SCA#2 exit
$E = 27.7$ MeV, $\sigma_t = 380$ fs, $\sigma_E = 250$ keV
$\varepsilon_x = 0.16$ mm-mrad, $\varepsilon_y = 0.13$ mm-mrad
Phase plot at the SCA #2 exit
Significant enhancement of the FEL gain by velocity bunching. Gain~40% is possible even with emittance growth during the bunching.
Simulation of XFELO (5 GeV with velocity bunching)

After the saturation:

- pulse duration \( \tau = 1.2 \) ps (FWHM)
- photons/pulse (intra cavity) \( N_p = 2 \times 10^{10} \)
- photons/pulse (extracted) \( N_p = 7 \times 10^{8} \)
2-Loop Design of 5-GeV ERL

HOM-damped cavity allows 2-loop configuration.

high threshold current of HOM BBU

TESLA (HOM:5×2)

ERL (HOM:6×2)
Possible Scheme for Combining ERL and XFELO

- 5 GeV ERL for SR use: accelerate 2 times
- 7.5 GeV recirculating linac for XFELO: accelerate 3 times

We can switch two operation modes by introducing an orbit bump having $\lambda_{rf}/2 = 11.5$ cm.

S. Sakanaka, talk at PF-ISAC (2010)
Growth of emittance and e-spread for 3-pass 7.5-GeV

1\textsuperscript{st}-loop: \( E=2.5 \text{ GeV}, \rho=8.66\text{m}, \ 2\times14\)-cell FODO
2\textsuperscript{nd}-loop: \( E=5 \text{ GeV}, \rho=25\text{m}, \ TBAx30\)-cell

\[ I_3 = 8.4 \times 10^{-2} (m^{-2}) \quad I_5 = 2.8 \times 10^{-3} (m^{-1}) \]
\[ I_3 = 1.0 \times 10^{-2} (m^{-2}) \quad I_5 = 4.6 \times 10^{-5} (m^{-1}) \]

<table>
<thead>
<tr>
<th></th>
<th>( \Delta \varepsilon_n )</th>
<th>( \Delta \sigma_E )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1\textsuperscript{st} loop (2.5 GeV)</td>
<td>8\text{pC/400fs}</td>
<td>20\text{pC/2ps}</td>
</tr>
<tr>
<td>incoherent SR</td>
<td>0.029 mm-mrad</td>
<td>34 keV</td>
</tr>
<tr>
<td>coherent SR</td>
<td>assumed to be compensated</td>
<td>37 keV</td>
</tr>
<tr>
<td>2\textsuperscript{nd} loop (5 GeV)</td>
<td>0.027 mm-mrad</td>
<td>130 keV</td>
</tr>
<tr>
<td>incoherent SR</td>
<td>assumed to be compensated</td>
<td>53 keV</td>
</tr>
<tr>
<td>coherent SR</td>
<td></td>
<td>16 keV</td>
</tr>
</tbody>
</table>

\[ \varepsilon_n = \sqrt{\varepsilon_i^2 + \Delta \varepsilon_c^2 + \ldots} \quad \varepsilon_n = 0.1 \rightarrow 0.11 \text{mm} - \text{mrad} \]

\[ \Delta \sigma_E = \sqrt{\Delta \sigma_{E,i}^2 + \Delta \sigma_{E,c}^2 + \ldots} \quad \Delta \sigma_E / E = 2 \times 10^{-5} \]

acceptable for FEL
Stability of SRF

Cornell LLRF System

Demonstrated:

- Exceptional field stability at $Q_L = 10^6$ to $10^8$
- Lorentz-force compensation and fast field ramp up
- Piezo microphonics compensation with ~20 Hz bandwidth

Energy stability $\ll$ FEL gain band width

$$\frac{1}{2N_u} = 1.7 \times 10^{-4} \text{ for } N_u = 3000$$

This requirement is fulfilled by current LLRF technology.
Conclusions

- Hard X-ray ERL can accommodate XFELO.
  - we can extend the frontier of X-ray beam parameters

- 0.1nm-XFELO is feasibly realized at
  - 5-GeV ERL with velocity bunching
  - 7.5-GeV beam from a 2-loop 5-GeV ERL
  - an ERL injector is shared, no major modification is needed

- XFELO can be installed either at a loop or a branch.
  - however, beam loss in a long narrow duct might be a problem for a XFELO in a loop

- In the Japanese collaboration, XFELO is considered as a part of 5-GeV hard X-ray ERL.