Laser assisted emittance exchange for ring lasing

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Outline

- Beam requirement for FELs
- Storage ring FELs
- Emittance exchange
- Laser assisted emittance exchange (LAEE)
- LAEE to enhance storage ring FEL performances
- LAEE to generate ultrahigh harmonic
Beam requirement in x-ray FELs

Electron slips back by one radiation wavelength after it travels one undulator period:

- Low geometric emittance: \( \frac{\varepsilon_n}{\gamma} \sim \frac{\lambda}{4\pi} \)
- Low energy spread: \( \frac{\sigma_E}{E} < \rho \)
- High peak current: \( L_G < L_R \)

~1 um emittance with ~1 MeV energy spread and ~kA peak current
Storage ring FEL

- Beams in storage ring
  
  Large emittance & Large energy spread & Low current

- PEP-X beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal emittance</td>
<td>0.6 mm mrad</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>0.6 mm mrad</td>
</tr>
<tr>
<td>Relative energy spread</td>
<td>1.14e-3</td>
</tr>
<tr>
<td>Peak current</td>
<td>270 A</td>
</tr>
<tr>
<td>Average beta function</td>
<td>5 m</td>
</tr>
<tr>
<td>Undulator period</td>
<td>3 cm</td>
</tr>
</tbody>
</table>

- Low power
- Poor transverse coherence
- FEL at <1nm is very difficult

Power gain length at 1nm
Emittance exchange

\[ \sigma_1 = R \sigma_0 R^T \]

Initial beam matrix

\[ \sigma_0 = \begin{bmatrix} \sigma_x & \sigma_{xz} \\ \sigma_{xz} & \sigma_z \end{bmatrix} = \begin{bmatrix} \epsilon_{x0} \beta_x & -\epsilon_{x0} \alpha_x & <xz> & <x\delta> \\ -\epsilon_{x0} \alpha_x & \epsilon_{x0} \gamma_x & <x'z> & <x'\delta> \\ <xz> & <x'z> & \epsilon_{z0} \beta_z & -\epsilon_{z0} \alpha_z \\ <x\delta> & <x'\delta> & -\epsilon_{z0} \alpha_z & \epsilon_{z0} \gamma_z \end{bmatrix} \]

Transfer matrix of a beam line

\[ R = \begin{bmatrix} A & B \\ C & D \end{bmatrix}, \quad A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, \quad B = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \]
Emittance exchange

\[ \sigma_1 = \begin{bmatrix} \sigma_{x1} & \sigma_{xz1} \\ \sigma_{xz1}^T & \sigma_{z1} \end{bmatrix} \]

with

\[ \sigma_{x1} = A\sigma_x A^T + B\sigma_{xz} A^T + A\sigma_{z1} B^T + B\sigma_z B^T \]
\[ \sigma_{xz1} = A\sigma_x C^T + B\sigma_{xz} C^T + A\sigma_{z1} D^T + B\sigma_z D^T \]
\[ \sigma_{xz1} = C\sigma_x A^T + D\sigma_{xz} A^T + C\sigma_{z1} B^T + D\sigma_z B^T \]
\[ \sigma_{z1} = C\sigma_x C^T + D\sigma_{xz} C^T + C\sigma_{z1} D^T + D\sigma_z D^T \]

Requirements for complete emittance exchange

\[ A = D = 0 \]

\[ \sigma_1 = \begin{bmatrix} B\sigma_z B^T & B\sigma_{xz} C^T \\ C\sigma_{xz} B^T & C\sigma_x C^T \end{bmatrix} \]

\[ \epsilon_{x1}^2 = |B\sigma_z B^T| = \epsilon_{z0}^2 \]
\[ \epsilon_{z1}^2 = |C\sigma_x C^T| = \epsilon_{x0}^2 \]
Emittance exchange

- Chicane + rf dipole cavity (incomplete exchange)

\[
\begin{pmatrix}
0 & 2L & kL & LkR_{s6} - \eta \\
0 & 2 & k & kR_{s6} \\
kR_{s6} & LkR_{s6} - \eta & 0 & 2R_{s6} \\
k & kL & 0 & 2
\end{pmatrix}
\]


- Two doglegs + rf dipole cavity (complete exchange)

\[
\begin{pmatrix}
0 & 0 & kL & LkR_{s6} + \eta \\
0 & 0 & k & kR_{s6} \\
kR_{s6} & LkR_{s6} + \eta & 0 & 0 \\
k & kL & 0 & 0
\end{pmatrix}
\]

Storage ring FEL

- Standard emittance exchange does not work well in storage rings

Large longitudinal emittance

\[ \varepsilon_{nz} = \Delta \gamma \sigma_z = 10 \times 3000 = 30000 \mu \text{m} \]

- After emittance exchange, beam transverse emittance (and the transverse beam size as well) is increased by orders of magnitude

- NO enhancement in FEL performances
Laser assisted emittance exchange (LAEE)

\[ E_x = \frac{E_0}{1 + (z/z_0)^2} \frac{2\sqrt{2}x}{w_0} \sin(2\pi(z - ct)/\lambda + \phi) \times \exp \left[ -\frac{x^2 + y^2}{w_0^2(1 + (z/z_0)^2)} \right] \]

\[ \sigma_z \sim \frac{\lambda}{10} \]

\[ s = 0 \quad \Delta x'(x, y, s) \approx k_s \]
\[ \Delta \gamma(x, y, s)/\gamma \approx k_x \]

\( \text{TEM}_{10} \) laser is equivalent to rf dipole mode cavity for the particles at \( s \sim 0 \)
LAEE (Gold particles in red)

Phase space after interaction with the TEM$_{10}$ laser

Before exchange

After exchange
Compact x-ray FELs

- **Soft x-ray FEL at 1.5 nm**
  \[ E = 1.2 \text{ GeV}; \ L_s = 15 \text{ m}; \ N_p = 3 \times 10^{11} \]

- **Hard x-ray FEL at 0.15 nm**
  \[ E = 3.8 \text{ GeV}; \ L_s = 30 \text{ m}; \ N_p = 5 \times 10^{10} \]

- Storage ring FEL
  - Apply LAEE to PEP-X

Small longitudinal emittance for the slices

\[ \varepsilon_{nz} = \Delta \gamma \sigma_z = 10 \times 0.5 = 5 \mu m \]

- PEP-X beam parameters

<table>
<thead>
<tr>
<th>Before LAEE</th>
<th>After LAEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupling parameter</td>
<td>10%</td>
</tr>
<tr>
<td>Horizontal emittance</td>
<td>1.2 mm mrad</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>0.12 mm mrad</td>
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<tr>
<td>Energy spread</td>
<td>5 MeV</td>
</tr>
<tr>
<td>Peak current</td>
<td>300 A</td>
</tr>
</tbody>
</table>

\[ L_G = 35m \quad \rightarrow \quad L_G = 8m \]
LAEE to enhance storage ring FEL performances

- PEP-X FEL performances with LAEE
  Increased power & Improved transverse coherence
Coherent harmonic generation (CHG) in storage ring

- Standard harmonic generation technique

Before chicane

\[ R_{56} \frac{\Delta E}{E} = \frac{\lambda}{4} \]

After chicane
CHG in storage ring

- Harmonic number limited by intrinsic large energy spread

Schematic of the coherent harmonic generation in Elettra storage ring

- Shortest wavelength achieved is 132 nm
- Highest harmonic number achieved is n=3
- 1 kHz coherent VUV source

- LAEE to enhance CHG in storage ring
  - Making full use of the extremely low vertical emittance

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</tr>
</thead>
<tbody>
<tr>
<td>Coupling parameter</td>
<td>1%</td>
</tr>
<tr>
<td>Horizontal emittance</td>
<td>1.76 mm mrad</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>0.0176 mm mrad</td>
</tr>
<tr>
<td>Energy spread</td>
<td>5 MeV</td>
</tr>
<tr>
<td>Peak current</td>
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</table>

LAEE $\rightarrow$ 43 keV
LAEE to enhance CHG in storage ring
LAEE to enhance CHG in storage ring

Bunching factor at n=100 is about 6%

1 kHz coherent soft x-ray source
Summary

- LAEE may allow one to generate beam with ultralow transverse emittance
- Help to realize an ultra-compact XFEL
- LAEE may be used to enhance the storage ring FEL performances
- LAEE may be used to extend the harmonic number of CHG in storage ring by two orders of magnitude

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Thanks!