Laser assisted emittance exchange to reduce the X-ray FEL size

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Outline

- Beam requirement for FELs
- Principles of emittance exchange
- Laser assisted emittance exchange (LAEE)
- An 1.5 Angstrom FEL driven by 3.8 GeV beam
- Timing and energy jitter
Beam requirement in x-ray FEL

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

~10 GeV beam with ~1 MeV energy spread and ~kA peak current

- LCLS: ~14 GeV; European XFEL: ~17.5 GeV
Motivation for compact FEL

- $$$
  - LCLS: 420 M $
  - European XFEL: 850 M Euros

- Space
  - SwissFEL, FEL at China, …..
Path to a compact FEL

\[ \lambda_r = \frac{1 + K^2 / 2}{2 \gamma^2} \lambda_u \quad K = 0.934 \times B(T) \times \lambda_u \text{ (cm)} \]

- Electron-radiation coupling requires \( K \geq 1 \)
- Small \( \lambda_u \), in-vacuum undulator
- Resistive wake field \( \sim a^{-2} \)
- Compact hard x-ray FEL with short period undulator
  - Moderate energy \( \sim 4 \text{ GeV} \)
  - Moderate peak current \(< 500 \text{ A} \)
  - Ultralow transverse emittance \( \sim 0.1 \text{ mm mrad} \)
  - Saturation length \( \sim 30 \text{ m} \) (undulator period \( \sim 1 \text{ cm} \))
Wake field effect in compact x-ray FEL

Spring-8 Compact Sase Source (SCSS)

Undulator period: 15 mm
Undulator gap: 3.5 mm

(a) Resistive Wakefield

Distance from Undulator Entrance (m)
**Emittance exchange**

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

**Initial beam matrix**

\[ \sigma_0 = \begin{bmatrix} \sigma_x & \sigma_{xz} \\ \sigma_{xz}^T & \sigma_z \end{bmatrix} = \begin{bmatrix} \epsilon_{x0} \beta_x & -\epsilon_{x0} \alpha_x & <xz> & <x\delta> \\ -\epsilon_{x0} \alpha_x & \epsilon_{x0} \gamma_x & <x'z> & <x'\delta> \\ <xz> & <x'z> & \epsilon_{z0} \beta_z & -\epsilon_{z0} \alpha_z \\ <x\delta> & <x'\delta> & -\epsilon_{z0} \alpha_z & \epsilon_{z0} \gamma_z \end{bmatrix} \]

**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

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

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

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

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

Requirements for complete emittance exchange

\[ A = D = 0 \]

\[ \epsilon_{x1}^2 = |B \sigma_z B^T| = \epsilon_{z0}^2 \]

\[ \epsilon_{z1}^2 = |C \sigma_x C^T| = \epsilon_{x0}^2 \]
**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)**

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

Limitations of the emittance exchange

- Longitudinal emittance is NOT small
  - LCLS beam: 250 pC
    
    \[ E = 6 \text{ MeV} \]
    
    \[ \sigma_z = 0.7 \text{ mm} \]
    
    \[ \varepsilon_{n,z} = \frac{\gamma \sigma_z \sigma_\delta}{E} = 1.4 \mu\text{m} \]
    
    \[ \sigma_\delta = 1 \text{ keV} \]

  - Transverse emittance is \(~0.5\) um
  - Short bunch might have CSR problem
    
    \[ \sigma_z = 70 \mu\text{m} \]
    
    \[ \varepsilon_{n,z} = 0.14 \mu\text{m} \]

- Timing and energy jitter problem
Laser assisted emittance exchange (LAEE)

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

$\sigma_z \sim \lambda/10$

$\Delta x'(x, y, s) \approx ks$

$\Delta \gamma(x, y, s)/\gamma \approx kx$

**TEM$_{10}$ laser is equivalent to rf dipole mode cavity for the particles at s~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
  - $E = 3.8 \text{ GeV}$; $L_s = 30 \text{ m}$; $N_p = 5 \times 10^{10}$

Effects of energy and timing jitter

- Standard emittance exchange scheme

- Timing jitter → wrong phase → non-zero kick → position jitter

- Energy jitter → wrong phase → non-zero kick → position jitter

Effects of energy and timing jitter

- Traditional emittance exchange scheme
  
  Timing/Energy jitter on the order of $\sigma_z$ and $\sigma_E$ will transform to transverse position/angular jitter on the order of $\sigma_x$ and $\sigma_x'$

- LAEE (timing jitter absorber)

Because the GOLD particles are defined by the laser, the timing and energy jitter of the beam will not affect the beam transverse position and divergence.
Summary

- LAEE may allow one to generate beam with ultralow transverse emittance
- Help to realize an ultra-compact XFEL
- NOT sensitive to energy and timing jitter

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